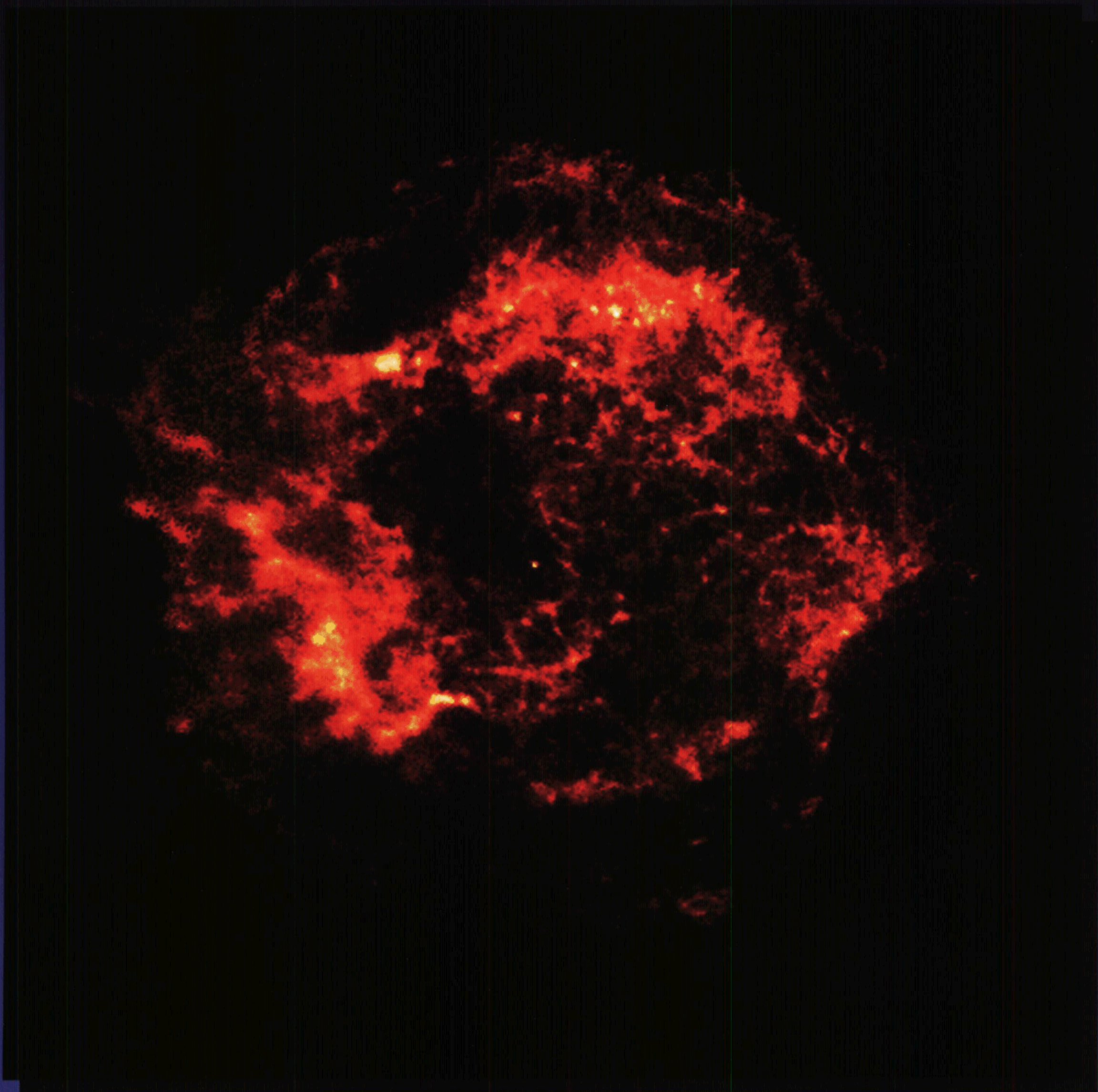
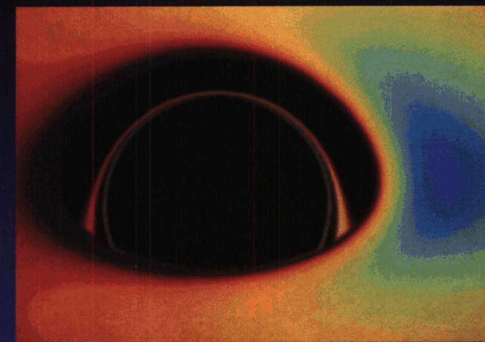
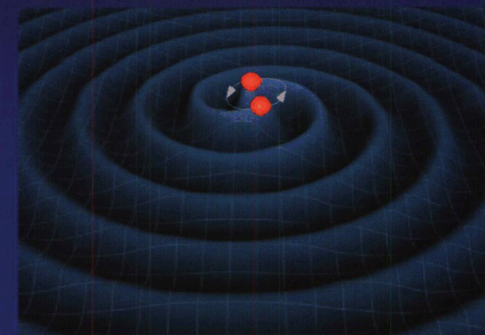
Cosmic Journeys

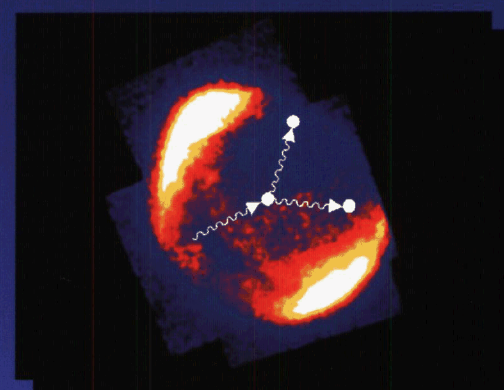
To the Edge of Gravity, Space, and Time

Structure & Evolution of the Universe Roadmap 2003-2023









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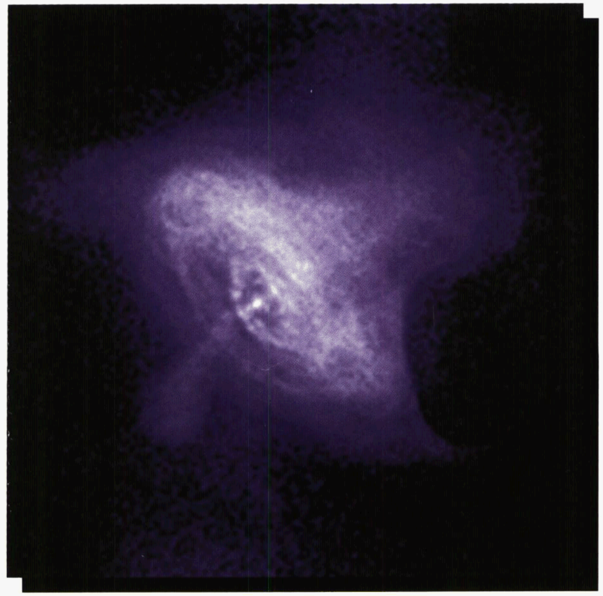
Structure and Evolution of the Universe Roadmap: 2003–2023



prepared by

The Structure and Evolution of the Universe Subcommittee of the
Space Science Advisory Committee
National Aeronautics and Space Administration

September 1999

Executive Summary

The Roadmap for the Structure and Evolution of the Universe (SEU) Theme embraces three fundamental, scientific quests:

- To explain structure in the Universe and forecast our cosmic destiny
- To explore the cycles of matter and energy in the evolving Universe
- To examine the ultimate limits of gravity and energy in the Universe

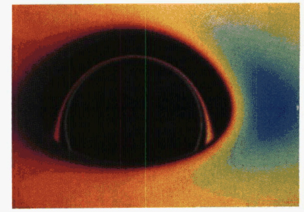
We develop these quests into six focused research campaigns:

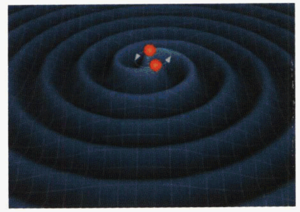
- Identify dark matter and learn how it shapes galaxies and systems of galaxies
- Explore where and when the chemical elements were made
- Understand the cycles in which matter, energy, and magnetic field are exchanged between stars and the gas between stars
- Discover how gas flows in disks and how cosmic jets are formed
- Identify the sources of gamma-ray bursts and high-energy cosmic rays
- Measure how strong gravity operates near black holes and how it affects the early Universe

These campaigns lead to a portfolio of future major missions of great scientific interest and popular appeal, strongly endorsed by the scientific community. Many have undergone significant initial study. Some are in a state of readiness that make them ideal candidates for the present Office of Space Science Strategic Plan; others may well feature in the next Plan. Each provides a golden scientific opportunity to advance our understanding of the Universe.

We have identified three top-priority near-term science objectives together with missions to accomplish these goals. The three problems span a diverse range of subdisciplines, of observational technique, of timescales, and of cost, and are thus complementary, forming a coherent core program for the SEU theme in the 2003–2007 timeframe.

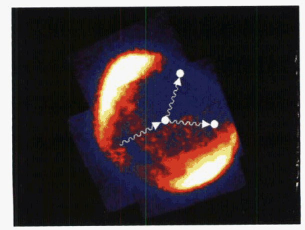
- Obtain precise measures of the chemical composition and physical conditions in objects ranging from the closest stars to the most distant quasars via X-ray spectroscopy of unprecedented sensitivity.





- Utilize, for the first time, gravitational radiation as a probe of supermassive black holes throughout the Universe, compact binary sources within our Galaxy, and a possible gravitational wave background, using a 5 million kilometer arm-length laser interferometer in space.

- Determine the nature of the highest-energy cosmic rays, one of the most important questions in this fundamental field, via a measurement of the characteristics of individual elements over a wide range of mass and energy, utilizing the International Space Station as a platform.



We also describe a small number of exciting missions which are strong candidates for new start status in the midterm, 2008–2013, pending technology development. These missions tackle fundamental problems through the entire electromagnetic spectrum, from the radio through gamma rays, and in many cases develop fascinating technologies with applicability not only elsewhere in NASA but outside of space science as well. Finally, we describe a set of "vision missions," which stretch our scientific imagination and set technology challenges for our field.

A vigorous program of education and public outreach will bring the wonderful array of past and current scientific achievements in this theme to the public.

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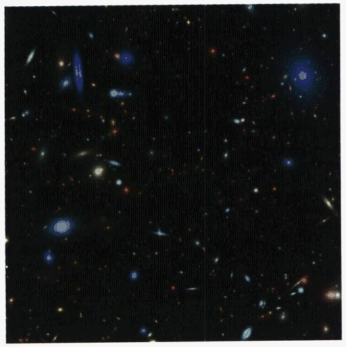
1 Introduction



The Universe contains billions of galaxies, scattered over vast reaches of space and time. These galaxies are profoundly dynamic systems of stars, gas clouds, and more. Radiation fields from the beginning of the Universe percolate through it even now, cooling as the Universe expands.

In one of these galaxies is a planet which we call home. This Earth performs an annual cycle around our local star, the Sun, which itself changes on longer timescales. This mixture of cycles and changes permeates the entire Universe, often on scales which completely transcend the human experience. If we gaze into the sky at night we can see the same patterns of stars named in antiquity. But these stars are actually in motion; if we could see the sky a million years from now, many of these constellations will have vanished.

The structure and evolution of the Universe is as fundamental to who and what we are as the structure and evolution of a society or a culture. It is not only the physical form with which the myriad pieces are assembled but the rules, relationships, and interdependence that determine their evolution. The interrelated life cycles and changes of all of these pieces and parts determine where we came from, and where we are going.

This document sets a strategy for space exploration to understand the structure and evolution of the Universe. This involves observations of physical phenomena at the limits of our understanding, operating on scales which challenge our imagination. In a sense these activities are the frontiers of the human interpretation of our existence. It is our goal to understand how our Universe, starting out with what we have come to call the “Big Bang,” composed entirely of hydrogen and helium, came to be the place that we now know, rich in the chemical elements out of which were formed stars, planets, and life itself. It is our goal to understand how gravity and nuclear forces contribute to both building and destroying pieces of our Universe, and the way that cycles of matter and energy have contributed to the diversity of the whole.

For ours is a Universe not just of gas and stars but of photons and magnetic fields, of molecules and atoms, of rocks and dust grains. It is a Universe of smooth waves and turbulent flows, of clouds and filaments, and of intense heat and extreme cold. A Universe whose quiescent parts provide counterpoint to the collisions and explosions, the flashes and jets. These components of the life cycle of our Universe are now superimposed upon the footprints and ashes of what came before.

The structure and evolution of the Universe is our story. We have seen, in the cosmic microwave background that permeates it, the fragmentation of the Big Bang into clumps that would later become clusters of galaxies. We have seen the infrared signatures of stars that are just forming inside dense clouds in galaxies like these, and we have measured the elements that were built up out of generations of stars like these that are now long gone.

While these discoveries of decades ago have been comfortably incorporated into our world views, our new tools provide us with surprises that will lift us to new levels of insight about our home. We now realize that our Universe may be made mostly out of material that doesn’t produce any light. We see flashes of gamma rays that are momentarily as bright as the rest of the entire Universe. Stellar systems can “shine” by gravitational radiation, which will provide intimate perspectives into the properties of black holes and neutron stars.

Our new discoveries on the path to understanding the structure and evolution of the Universe need names that did not even exist a few decades ago. Words like "black hole," "quasar," and "Big Bang" have been thoroughly adopted by our culture, both as highlights of our explorations as well as metaphorically. In addition to the scientific accomplishment, it is the spirit of exploration and the sense of fascination engendered by these pursuits that drives our efforts. This work inspires the imagination and excites the spirit. Through these efforts, we reach out to frontiers that are both popularly accessible and scientifically productive. We reach out to frontiers that are real places, where we see Nature behaving under conditions that do not exist on Earth.

This SEU Roadmap guides our efforts to explore the cosmic frontiers of gravity, space, and time. The development of this Roadmap is based on the major unsolved mysteries about the structure and evolution of the Universe. Implicit in it is a careful assessment of our technical and analytical capabilities. The recommended mission portfolio results from a critical study which tries to provide the highest scientific value, popular appeal, and richest return, while remaining sensitive to budgetary realities. These missions are the new tools that will continue to elevate our perspective and challenge our creativity.

It is important to note that these missions represent the promise of a wealth of astronomical data. Experience has clearly shown that the scientific value of these data extends well beyond that foreseen by the mission science teams, and that a strong data analysis program additionally supporting theoretical investigations is the best guarantee of productive interdisciplinary work.

The priorities in this Roadmap extend and update those from the previous one. While three years has provided us with a wealth of new understanding and mission successes, it is with satisfaction that we note the consistency of our outlook. In addition, this Roadmap unveils several completely new and promising mission concepts that give an invigorating long-term picture for the SEU Theme. It is these differences and additions that, as pointed out in the earlier SEU Roadmap, are indicative of a vibrant scientific discipline.

As before, this Roadmap also benefits from an extensive heritage of diverse prior studies, including those of the National Research Council. The Astronomy Survey Committee of the NRC, at present preparing recommendations for the coming decade, has provided a timely community discourse on ground-based, as well as space based astronomy which helped with the development of this plan. This Roadmap serves not only to define a portfolio of missions with a broad science range for the coming decade but also to encourage their technical validation, and refine their scientific rationale, so that they can be subjected to careful peer review.

Astronomy has been revolutionized by observing from space, away from the obscuring effects of our atmosphere. We are opening up to view the entire electromagnetic spectrum, observing waves with lengths from kilometers to a hundredth the size of a proton. We are watching things change on timescales from milliseconds to decades. In addition to the light that we analyze, we are exploiting non-electromagnetic information channels like cosmic rays, neutrinos, gravitational radiation, and direct inspection of interstellar material. We are truly fortunate to be living at a time when our understanding of the Universe, and the frontier that it represents, is changing from the stuff of myth and legend to a comprehensive description of its structure and evolution, together with an appreciation of its final destiny.

The Cosmic Background Explorer (COBE) made the first observational link between structure in the ancient and modern Universe. The Hubble Space Telescope (HST) has found evidence that massive black holes probably exist in most galaxies. The identification of the optical counterparts of gamma-ray bursts, enabled by mul-

tiple spacecraft including the Compton Gamma Ray Observatory (CGRO), has provided a major leap forward in our understanding of these violent phenomena, by placing them at cosmological distances and consequently huge intrinsic luminosities. Compton has also discovered extraordinarily high-energy and long-lived photons in some of these bursts, as well as unveiled a new class of startlingly powerful galaxies, gamma-ray blazars. The Rossi X-ray Timing Explorer (RXTE) has discovered a rich spectrum of pulsations from accretion disks in binary X-ray sources. The Japanese-US X-ray satellite, ASCA, has seen swirling disks of gas around the massive spinning black holes in active galactic nuclei. The list goes on and is updated on a weekly basis.

The immediate future is even brighter. The recently launched Chandra X-ray Observatory will resolve the diffuse X-ray background to determine the dominant X-ray emitters in the Universe. It will also start to show us how gas accretes onto black holes and map, in detail, the giant clusters of galaxies to give us quantitative measurements of the extent of large-scale structure. Another recent launch, the Submillimeter Wave Astronomy Satellite (SWAS) has begun to reveal that our Galaxy teems with tenuous water molecules. The Microwave Anisotropy Probe (MAP) will soon measure the fluctuations in the microwave background on angular scales much smaller than COBE and enable us to measure directly the size and contents of the 300,000 year old Universe. Chandra, ASTRO-E, and XMM will open new eras in high resolution X-ray spectroscopy, observing objects from the nearest stars to the most distant quasars. Explorers such as HETE-2 and GALEX will tackle specialized but vexing problems in astrophysics, in the new "smaller, faster" paradigm.

In order to guide this process, the Structure and Evolution of the Universe Subcommittee (SEUS) has produced this Roadmap, an integrated long term vision of the science program encompassed by its theme which recommends a set of missions to be developed and constructed in the next century. We have tried to look forward to 2020 and to anticipate what might be possible over this epoch. In formulating this Roadmap, we have tried to retain flexibility to respond to new discoveries, technical innovations, and international opportunities.

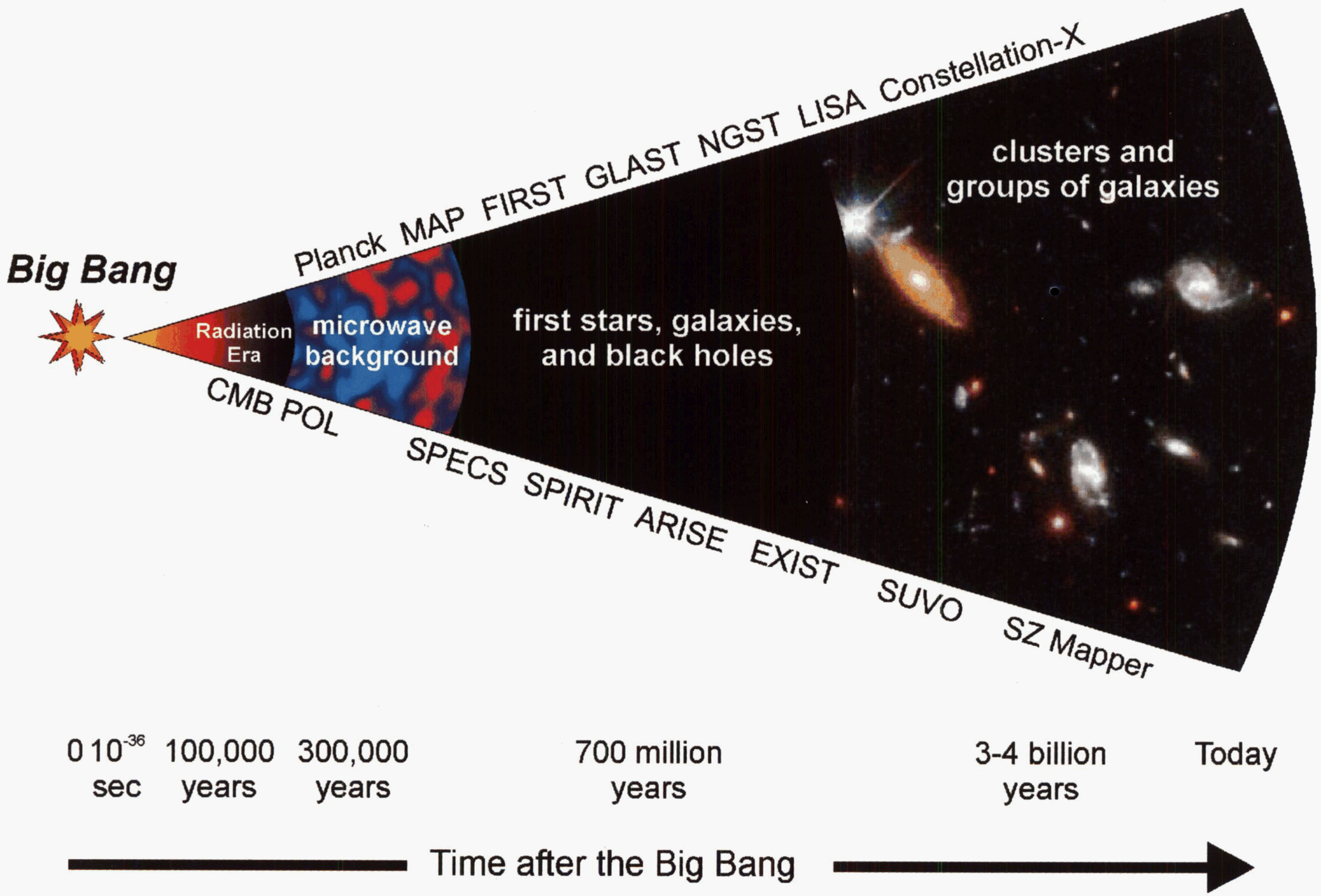
In organizing this document, we have formulated three fundamental "Quests" which are presented below. These are our overarching goals of broad scientific and popular appeal. To be more specific about our goals, we break down these quests into six more focused Campaigns that pose general questions that can be addressed over the next 20 years. We then present the mission portfolio that is needed to fulfill these campaigns. Our Roadmap includes an assessment and specification of the technical groundwork that is required for timely completion of these campaigns, and also a prescription for public outreach, to share with every citizen the excitement and inspiration that this work instills.

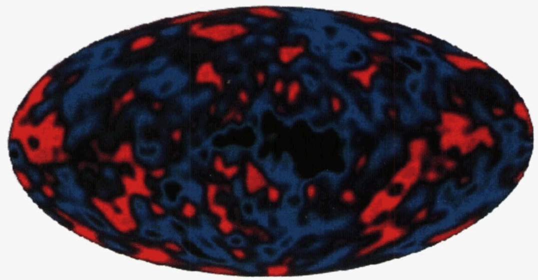
2 Quests

2.1 To Explain the Structure of the Universe and Forecast Our Cosmic Destiny

The expansion of the Universe, observed abundances of light elements, and the cosmic microwave background together imply that our Universe was born in a big bang which we now know must have been about 12 billion years ago. This discovery raised several obvious new questions: What is the origin of the expansion? How exactly did this big bang transpire? What will be the ultimate fate of the Universe? Will it expand forever or eventually recollapse? What is the shape or geometry of our Universe? Is it flat like a piece of paper? Or curved like the surface of a sphere or potato chip? Where

The Journey Through Cosmic Time





The microwave temperature of the sky measures incipient structures in the 300,000-year-old universe

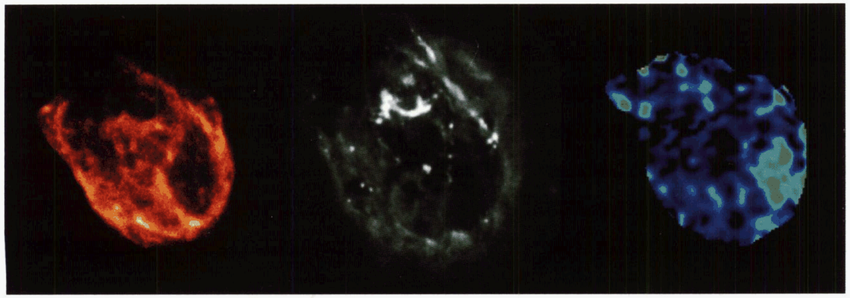
did large-scale structures such as galaxies and galaxy clusters come from? These questions have remained unanswered for almost seventy years. However, we have in recent years developed mature and intriguing theories that provide solutions to these cosmic enigmas as well as a suite of observations that will test these ideas with unprecedented precision.

We know from observations of the cosmic microwave background (CMB) radiation, the isotropic high-frequency radio emission discovered in 1964 by Arno Penzias and Bob Wilson, that the early Universe was very smooth. This radiation was last scattered from the universal primordial plasma when the Universe was roughly 300,000 years old. The COBE discovery of tiny fluctuations in the CMB temperature implied the existence of some tiny density perturbations and thus confirmed the simplest hypothesis for the origin of large scale structure; i.e., that it grew from tiny primordial density perturbations. However, we would still like to understand in far more detail how these relatively simple initial conditions evolved into the galaxies, clusters, stars, and planets that characterize our Universe today. What is the dark matter known to dominate the mass of the Universe? What was its role in the origin of the richness of structure in the Universe today? When did gravitationally collapsed objects first form? Was the growth of structure bottom up, with stars and star clusters forming first and then gravitating together to form galaxies and clusters of galaxies? Or was it top down, progressing from huge walls and filaments evident in the local distribution of galaxies through galaxy clusters and groups to the galaxies and stars themselves?

Our quest is to address these questions with precise new observations. More sensitive maps of the CMB temperature and polarization will reveal the initial conditions (at age 300,000 years) for structure formation. The history of the Universe from that time until today will then be filled in by observations of remnants of the earliest collapsed objects with a complementary array of telescopes that span the electromagnetic spectrum from gamma-rays to the radio, and with gravitational-wave detectors.

In the course of these endeavors, it is likely that we will finally determine the geometry of the Universe and the amount of baryons, dark matter, radiation, neutrinos, and vacuum energy that it contains and thereby be able to forecast the ultimate fate of the Universe. These measurements will also test intriguing ideas that link the origin of the Universe to new fundamental high-energy physics. Remarkable as it may seem, such observations may eventually provide an avenue towards probing new fundamental physics at energies orders of magnitude beyond those accessible at accelerator laboratories, and they may provide a window to the Universe at times as early as 10^{36} seconds after the big bang!

2.2 To Explore the Cycles of Matter and Energy in the Evolving Universe



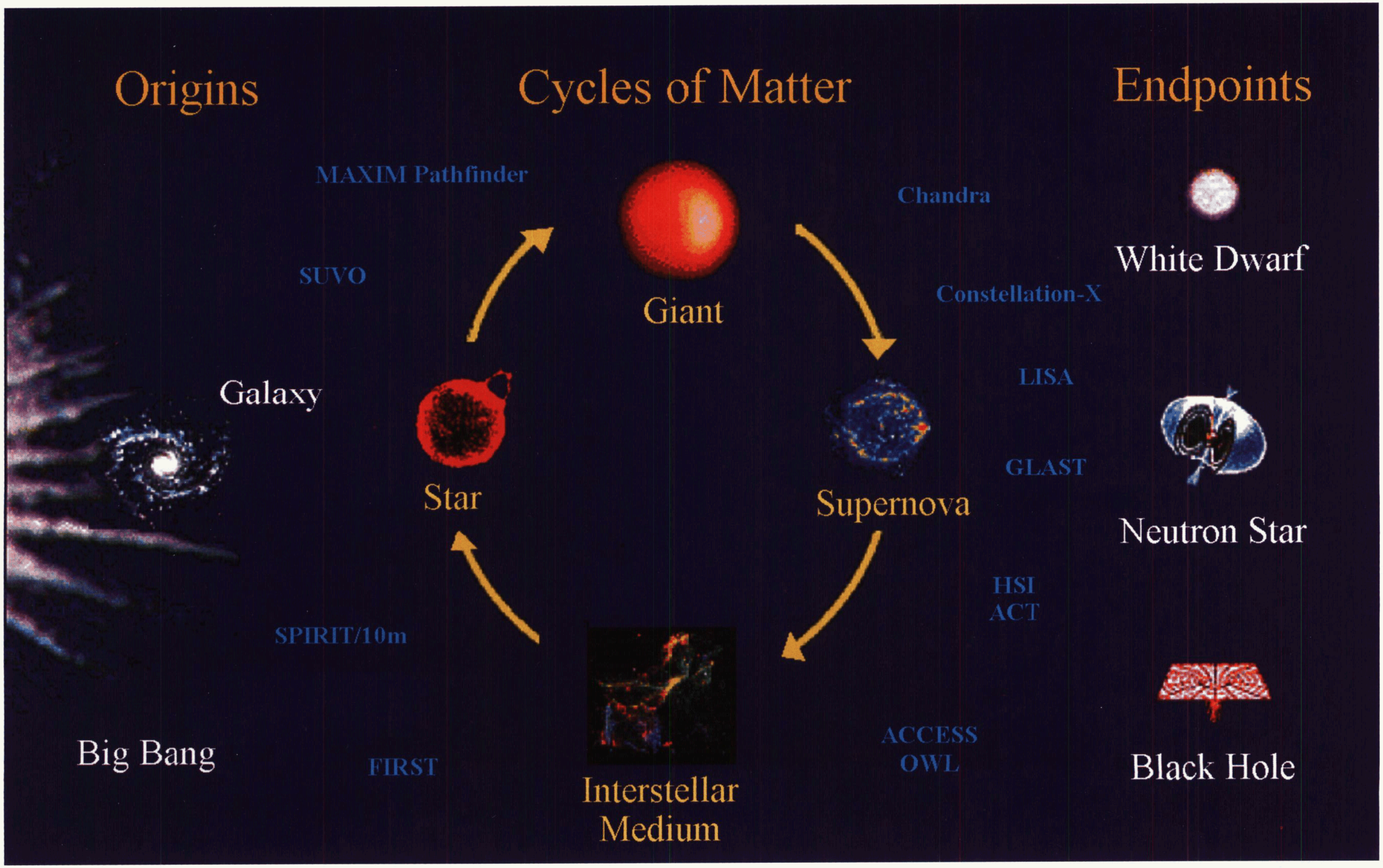
Supernova explosions are the main source of energy for the interstellar medium. The remnant of N132D is shown here in a ASTRO-E X-ray image, visible light, and radio.

Our cosmic neighborhood, our Galaxy, and the Universe of galaxies have such complex webs of interactions that astronomers think of them much as biologists think of ecosystems, tracing the flow of matter and energy from one form to another. Stars have their origins in dense gas clouds, which condense and fragment to form clumps of stars with a range of masses. For a star, mass is destiny—the low mass stars slowly fuse hydrogen into helium, while massive stars burn fiercely for a brief cosmic moment. Stars about one half the Sun's mass or less have a lifetime which is at least as long as the present age of the Universe: the oldest stars in the Milky Way Galaxy contain a sample of the Universe from some 12 billion years ago. These stars show that our Galaxy was once very poor in the heavy elements out of which planets, spacecraft, and astronomers are made. More recently formed stars, like the Sun, have inherited a legacy of atoms that was created in the massive stars that lived out their short cycles more than 5 billion years ago. Massive stars make essentially all of the elements of our world—oxygen, calcium, iron—and they blast these new elements into the gas between the stars as they end their lives in supernova explosions. In these violent events, a single dying star, as it undergoes a catastrophic collapse into a neutron star or black hole, shines as brightly as a billion Suns, while accelerating cosmic rays, forming cosmic dust, and stirring the magnetic field between the stars. This is the major source of energy for the interstellar medium. The accumulated products of all these complex events become the material for new stars which form from the densest regions of the interstellar gas. In these dusty and obscure venues, the atoms can combine into molecules, including organic molecules related to life. Understanding how these complex events are related, from nuclear reactions through the formation of stars and their planets, is a prerequisite to understanding the origin of life in the Universe.

Lower mass stars like our Sun evolve more sedately. As they run out of hydrogen fuel in their cores, they slowly expand to become "red giants," relatively cool, very large stars; when the Sun becomes a red giant in some 5 billion years, it will expand to engulf the inner planets of the Solar System. In the red-giant phase, mass flows off the surface of stars in "stellar winds" that are the major source of matter for the interstellar medium. At the end of the red-giant phase, the star itself collapses to become a hot, planet-sized "white dwarf" which slowly cools as it radiates away its stored energy.

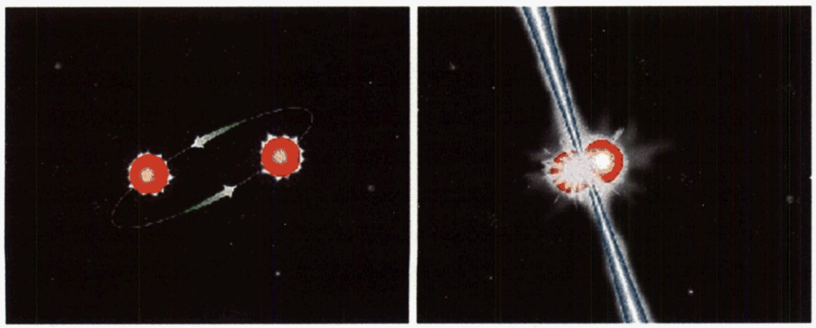
We are just beginning to learn how similar considerations apply to the larger scale phenomena of galaxy formation, and the interaction between galaxies and the intergalactic gas. Like the ancient stars that give a clue to chemical evolution in our Galaxy, quasars are ancient events that may signal the formation of galaxies when the Universe was less than one-fifth its present age. Quasars are probably supermassive black holes at the cores of nascent galaxies. They illuminate the chemistry of the intergalactic gas, heat it, and

The Journey of Matter and Energy



affect subsequent star formation. As stars are born and die in galaxies, and as galaxies collide and merge, these violent events sweep the accumulated gas into the space between galaxies. Recent X-ray observations show this ancient gas and allow us to begin to trace the effects of stars on the chemistry of the Universe.

2.3 To Examine the Ultimate Limits of Gravity and Energy in the Universe



Colliding neutron stars radiate energy in gravitational waves and may create bright flashes of light.

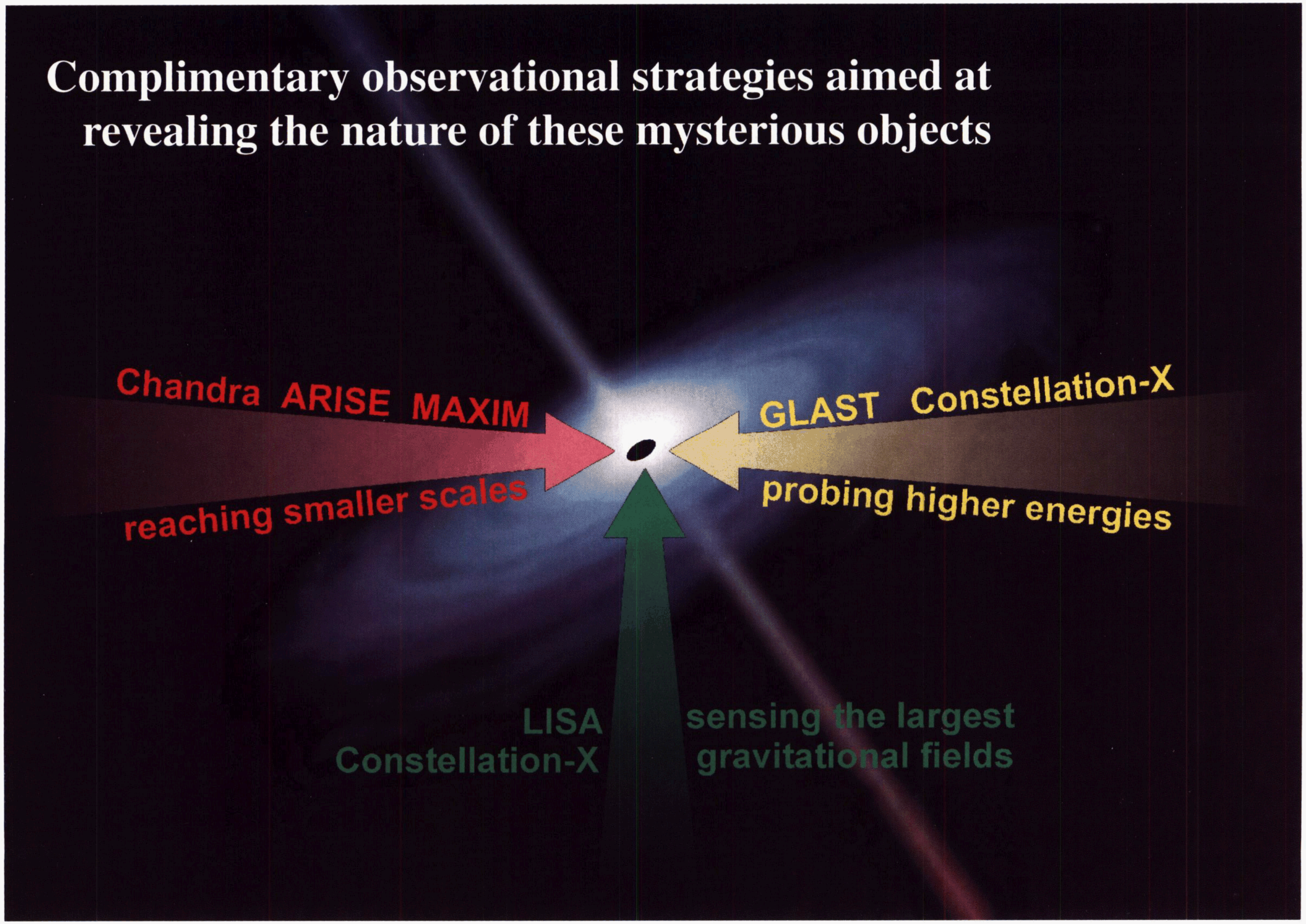
We now know that massive stars evolve relatively rapidly to form compact objects, known as white dwarfs, neutron stars, and black holes. The density of matter at the center of a neutron star exceeds that of atomic nuclei and is some 45 orders of magnitude greater than that of intergalactic space, which is orders of magnitude smaller than the most tenuous vacuum that can be made on Earth. Other quantities show similarly huge ranges—the magnetic field of a neutron star may be as high as 10^{14} G. while that in intergalactic space is certainly less than 10^{-7} G (and may be much smaller than this). The temperature when a neutron star is formed is about 10^{10} K, but the temperature of deep space is only 2.7 K. The kinetic energy of individual atomic or nuclear particles extends from about 10^{-3} eV for atoms in the cold, interstellar gas to over 10^{20} eV for the highest energy cosmic rays. Because of these extremes, the quest to understand the Universe is not an easy one, for we cannot create experiments in laboratories on Earth with the same conditions. But these cosmic laboratories permit astrophysicists to perform unique, passive experiments that constrain our physical theories of matter under extreme conditions.

Cosmic matter at high densities may be probed in many ways. For example, as a newly formed neutron star cools, it may be observed as a hot object in X-rays. Matter falling onto a neutron star also heats up to a high temperature and also radiates in the X-ray band. It will also spin rapidly, but then progressively slow down. This slowing causes cracking in the interior of the star, resulting in spin-ups of the rotation speed. These spin-ups can be monitored from observations of the radio and X-ray emission and tell us about the hidden interior of the star.

In another example, much of the focus in fundamental physics over the past 50 years has centered on observing elementary particles at the highest energies attainable by terrestrial particle accelerators. The Universe provides its own natural particle accelerators that can accelerate protons to energies over ten million times larger than those attainable on Earth. We can observe their interactions with matter as they impact our atmosphere.

There are also extremes of gravity, especially black holes, where the gravitational potential well becomes so deep that light is unable to escape. The correct description of matter under these conditions involves the general theory of relativity, which is largely untested

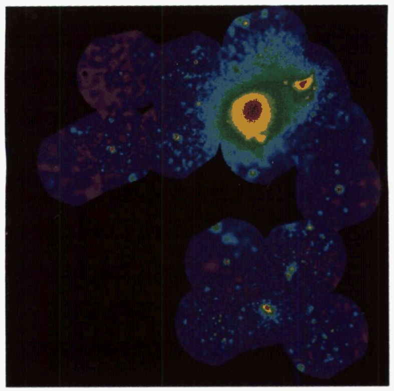
The Journey to a Black Hole



under conditions when the gravitational forces are very strong. In addition, the theory of relativity predicts the existence of gravitational radiation, ripples in the fabric of spacetime itself. Observations of gravitational waves will allow new tests of relativity theory and also give us fundamentally new astrophysical information about the high velocity, strong-gravity regions where these waves are generated.

3 Campaigns

3.1 Identify Dark Matter and Learn How It Shapes Galaxies Systems of Galaxies



Giant clusters of galaxies form in gravitational potential wells dominated by dark matter. These dark matter halos extend well beyond the observed galaxy population. They can, however, be mapped in the X-ray by observing hot, gravitationally bound gas, as in this ROSAT image of the Virgo Cluster.

One of the most striking discoveries of contemporary astronomy has been that most of the mass of the Universe is in a form that we cannot see. It is called dark matter and we do not know its nature. We can, however, detect it through the effects of its gravitational field and, in an indirect way, this may allow us to probe it. There are three distinct environments where this may be possible, individual galaxies, clusters of galaxies, and the early Universe at the time of recombination.

If galaxies are dominated by dark matter, then they can be thought of as essentially invisible gravitational potential wells in which stars follow complex orbits moving with characteristic speeds of about 300 km/s. In addition to the stars, elliptical galaxies contain hot, X-ray emitting gas that extends to radii well beyond where stars can be observed. By mapping the density and temperature of this hot gas, one can develop a reliable mass model of the galaxy and trace the dark matter distribution to very large radii.

On even larger scales, clusters of galaxies are complex, multi-component systems with hundreds of galaxies, a hot intracluster medium, and dark matter evolving in a tightly coupled manner. As they are dynamically relatively young systems, their study furnishes fundamental insights into the formation of large-scale structure in the Universe, especially if they can be observed at large distances, when the Universe was much younger than its present age. This is possible because these clusters still carry the imprint of the density fluctuations from which they grew. In addition, since clusters are massive and relatively rare objects, they form only from fairly high peaks in the underlying density field. Observing the abundance of massive clusters to measure the incidence of these peaks is a powerful discriminator for different cosmological theories. Furthermore, an inventory of their mass components should be a good reflection of the primordial mix. By combining X-ray measurements with the theory of big bang nucleosynthesis, one can estimate the mean density and dark matter content of the Universe. A further cosmological clue comes from the incidence of substructure in these rich clusters. If it is low, then clusters are dynamically old and the Universe is of relatively low density.

There also is a quite different approach to measuring the gas distribution and consequently the dark matter content of rich clusters. This involves measuring the small change that the hot gas produces

in the apparent temperature of the microwave background radiation—the so-called Sunyaev-Zeldovich effect. This is caused by scattering the background microwave photons to higher frequencies by the hot electrons in the cluster. This effect has been convincingly detected in observations from the ground. However, to measure it well in young and very distant clusters will require observations from space.

Cosmic background fluctuations have been seen by the COBE satellite coming from the epoch when ionized hydrogen changed into atomic hydrogen, when the Universe was 300,000 years old. These fluctuations can be used to obtain a quite different measurement of the matter content of the Universe. The fluctuations themselves are like giant sound waves that travel with a speed that depends upon how much mass is present. The observed fluctuations are larger when there is a coincidence between the period of the waves and the time it takes the photons to free themselves from their electron rich environment. This is known as the acoustic peak, and ultra-sensitive measurements of the cosmic background can be used to locate it and translate its size and angular scale on the sky into a direct inventory of the contents of the ancient Universe. This can be combined with observations of the modern Universe that are directed towards a similar goal. One of the greatest hopes of contemporary astronomy is that these two, essentially independent, approaches will be found to be concordant, thereby validating our theory of cosmology. This program is one of several strong linkages between the SEU and ASOPS themes and completing it also will require the full deployment of space-based infrared telescopes as well as ground-based optical telescopes.

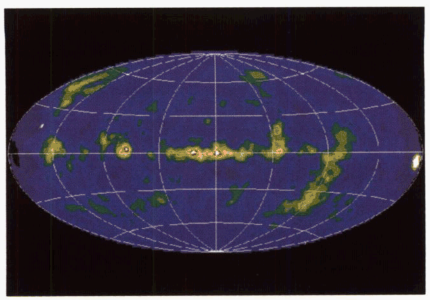
Through approved missions including MAP, as well as investigations with HST and Chandra, we should have, early in the next decade, a good understanding of the primary cosmological parameters including the age and scale of the Universe and its mass density, including both the baryon fraction and the value of the cosmological constant. If this optimism is well-founded, we will have a framework to lay out the more detailed, fossil record of how stars, galaxies, and large scale structures form and evolve. Crucial to this endeavor will be measurements of the distribution of the mass around galaxies and clusters of galaxies and how these change with cosmic time. Since most of the matter is dark and resides in the outermost parts of these entities, it will be necessary to trace the gravitational potential wells by studying the hot X-ray emitting gas in galaxies and clusters, measuring both its distribution and its temperature in some detail. This will require the deployment of high angular resolution X-ray imaging telescopes and a fine wavelength resolution spectroscopic mission. To measure cluster evolution requires mapping the gas and dark matter in individual high redshift clusters formed when the Universe was a fraction of its present age and this imposes the additional requirement of high sensitivity.

Of equal importance is direct observation of very distant galaxies that can identify the epoch of galaxy formation. This is most naturally carried out at optical and near infrared wavelengths and is a prime motivation for the Next Generation Space Telescope (NGST). However, a typical spiral galaxy radiates a quarter of its bolometric luminosity in the far infrared. Indeed many galaxies emit most of their radiation in the far infrared and submillimeter and may only be observable at these wavelengths. Observations of this part of the spectrum are an excellent method for finding high redshift galaxies that complement searches that will be made in the near infrared using NGST. Again we see a strong connection to one of the quests of the ASOPS Roadmap.

This campaign has so far assumed a standard model of cosmology that attributes structure formation to gravitational instability in cold

dark matter. There is an alternative view that would be of great interest to physicists, if it turns out to be correct. This is that phase transitions in the very early Universe left it scarred with a variety of topological defects, rather like the dislocations and grain boundaries that interrupt the crystal structure of a rapidly cooled metal, and it is these that are responsible for the structure that we see. As yet we have no evidence for the existence of these defects and future microwave background observations should settle the matter. However, it is quite possible that the defects will decay into ultra high energy cosmic rays ($E > 10^{20}$ eV). Measurements of the energy spectra of these highest energy cosmic rays would then tell us about particle physics at even higher energies.

3.2 Explore Where and When the Chemical Elements Were Made



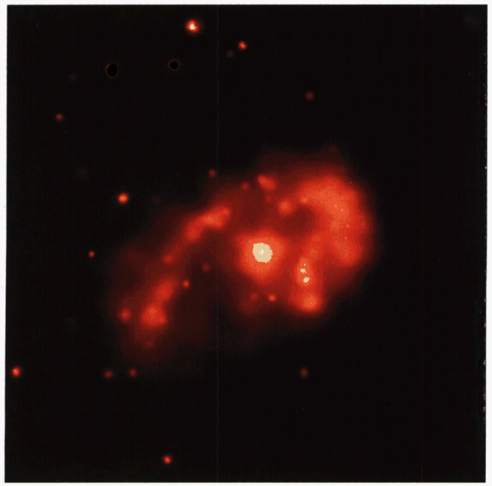
Spectroscopic observations in many parts of the electromagnetic spectrum, including gamma rays (shown in this COMPTEL map), can test theories of how the elements are made and disseminated.

We have known for nearly 40 years very generally how the chemical elements were made. Hydrogen, helium, and trace amounts of a few other light elements were made mostly in the first few minutes of the expansion of the Universe; the remainder are products of nuclear reactions occurring in stars and supernova explosions. Indeed, the theory of stellar evolution is one of the triumphs of contemporary astrophysics. With certain fascinating exceptions, we understand how a star evolves and shines as it ages from youth to senescence, all the while converting hydrogen and helium fuel into heavy elements. These heavy elements are released by stellar winds and supernova explosions and spread throughout the interstellar medium where they cool and collapse under the action of gravity so that new generations of stars can form. The bulk material of our solar system, including the Sun, Earth, Moon, and meteorites, is a sample of the local interstellar gas mix 4.6 billion years ago. By contrast, cosmic rays sample galactic material that was accelerated relatively recently, about ten million years ago. We can measure the relative abundances of the different elements and their isotopes directly within our solar system through cosmic rays, and spectroscopically in stars and elsewhere and compare with the results of detailed nuclear physics and stellar structure computations. In general such computations have successfully matched the observations—even when, as in certain cosmic ray elements, isotopic abundances are strikingly different from those found in the bulk material of the solar system. Further important tests await isotopic measurements of rarer cosmic-ray elements, and spectroscopic observations in many parts of the electromagnetic spectrum from the submillimeter and far infrared to the X-rays and gamma rays.

We also need to understand just where and when chemical evolution happened during the lifetime of a typical galaxy like our own. One way to explore the processes of chemical evolution is to observe our galactic neighbors. The traditional method is to use stellar spectra which tell us about the composition of selected stars. We anticipate that giant ground-based optical telescopes together with complementary observations from space will enable astronomers to perform these abundance analyses on more distant and consequently younger galaxies. However, this technique can only provide part of

the information and is subject to strong biases. Several complementary approaches must be used to get the full picture.

One of these involves high resolution X-ray spectroscopy. The first X-ray images of elliptical galaxies changed the widely held view that they were gas-free. Instead they showed that hot gaseous coronae with temperatures of 10^6 K and gas masses up to $10^{10} M_{\odot}$ surround these galaxies. Since this hot gas contains the fossil record of past generations of stars, spatially resolved X-ray spectroscopy can be used to determine the earlier history of star formation and supernova activity in these galaxies.



The star Eta Car, shown here in this Chandra X-ray image, is shrouded in a rapidly expanding cloud of dust. Much of the stellar emission is absorbed by this dust and re-radiated at far-IR and submillimeter wavelengths.

Another approach leads us to consider the role of interstellar dust. A significant fraction of the heavy elements created by stars condense into tiny grains, typically smaller than a micron, known as interstellar dust. At optical and near infrared wavelengths, this dust is an impediment to observation because it makes galaxies opaque, preventing us from easily seeing into them, and distorting their spectra in ways that are hard to quantify. However, when we look at these same galaxies at far infrared and submillimeter wavelengths, we see the dust as a bright source. All the optical and ultraviolet radiation absorbed by the dust causes the galaxies to glow at these wavelengths. We can then see these galaxies out to large distances and, indirectly through measuring their dust content, understand their stellar histories.

A novel approach to studying interstellar dust has recently become possible in terrestrial laboratories. A small fraction of the refractory grains within meteorites have been shown to be of presolar origin. Tiny grains of graphite, silicon carbide, oxides of aluminum and titanium, and other refractory minerals have widely varying isotopic abundances dramatically different from those found everywhere else in the Solar System. The isotopic abundances are typical of those seen spectroscopically, and predicted theoretically, around various kinds of evolved stars and supernovae. Further study of such grains will be valuable for understanding the chemical evolution of the Galaxy. These laboratory studies of meteorites which are formally the province of the ESS theme are, nonetheless, of great relevance to this campaign.

Turning to our local neighborhood, we know of several hundred individual remnants of supernova explosions that occurred over the past tens of thousands of years in our own and neighboring galaxies. These are seen as expanding spheres of hot gas. It is possible to measure the abundances of individual elements through the X-ray and gamma-ray lines that they emit before this gas gets mixed with the general interstellar medium. At present, it is only possible to detect the most common elements. However future observations should give us a good picture of the formation of essentially all of the elements between carbon and zinc. Recently, a new supernova remnant from a stellar explosion approximately 900 years ago was discovered in the Vela region of the sky through its gamma-ray and X-ray emission.

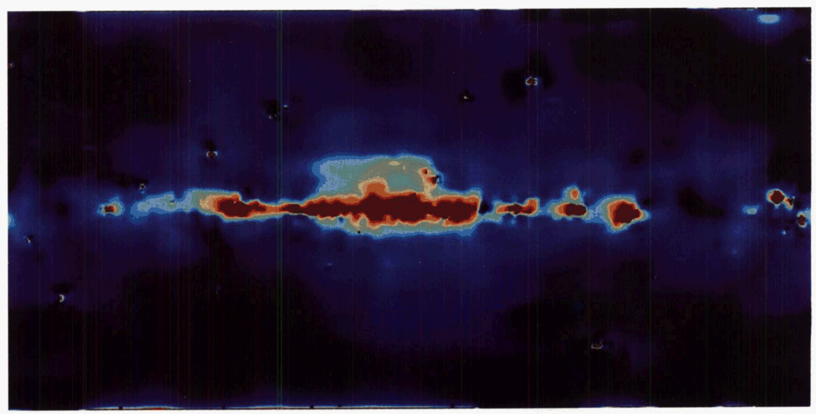
Another way to monitor the recent formation of elements is to observe the products of radioactive decay in our own Milky Way

Galaxy and its satellites. This can be done using gamma-ray observations of the decay products of short lived nuclei like ^{56}Co, as happened with the bright SN 1987A in the Large Magellanic Cloud or of longer-lived species like ^{26}Al throughout the interstellar medium of our Galaxy, which measures supernova activity over the past million or so years. Observations of other long-lived radionuclei, such as ^{60}Fe, will add to the understanding of the sites of nucleosynthesis. The gamma rays provide a direct probe of the process of element formation in supernova explosions. They are also highly penetrating radiation and therefore allow observations to be made deep into the enshrouding gas of the explosion. Observations of the 511 keV line of positron annihilation indicate large production of positrons, the antimatter counterparts to electrons, very likely from decay of radioactive nuclei, but better mapping of this line is required to understand the origin of these positrons.

We have a fairly good explanation of how stars end their lives. By contrast, our understanding of how stars are formed is literally shrouded in mystery, thanks again to the effects of interstellar dust. The sites of star formation are mainly the giant molecular clouds which are dense and quite opaque at optical wavelengths. However, when we turn to the far infrared, submillimeter, and X-ray portions of the spectrum, the clouds become transparent and allow us to observe what is actually happening. We find that the gas is able to form a large variety of exotic molecules typically not found in terrestrial chemistry laboratories. By making careful spectroscopic study of all the different lines that these molecules form, it should be possible to understand where and under what conditions stars can form and what determines whether these stars are massive or small.

Although stars generate their radiation through thermonuclear reactions, protostars have not yet begun to burn hydrogen and instead derive their energy from gravity as the star contracts. Far infrared observations can detect thermal radiation from the dusty cocoons around embryonic stars. Infrared spectroscopy also will determine the density and temperature as well as the composition and size of the dust particles in the proto-planetary disks around the forming stars. Submillimeter spectroscopy can determine motions in star-forming molecular clouds. Since new stars often form in clusters, good spatial resolution also is necessary to isolate the properties of individual sources. Pre-main sequence stars often emit X-rays, which through ionization of the gas in the cloud influences further star formation. These studies are crucial to understanding the origin of extra-solar planets, demonstrating another important connection to the ASOPS theme.

3.3 Understand How Matter, Energy, and Magnetic Fields are Exchanged Between Stars and the Gas Between Stars



The Milky Way's gamma ray halo, as observed by CGRO/EGRET.

X-ray observations of our Galaxy show a wealth of structure in the interstellar medium, such as deep absorption along the Galactic plane

and strong emission from very ancient supernova remnants. Since it is through supernovae that both heavy elements and substantial energy are injected into the interstellar medium, studies of supernovae and their remnants are crucial for understanding these processes. X-ray observations have provided much of our current knowledge of the physical conditions of the hot gas in supernova remnants, and have identified an important phase of the interstellar medium. Chandra, with its high spatial resolution, broad energy range, and excellent spectroscopy, will map the heavy element distribution in individual supernovae remnants, both in our Galaxy and in the Magellanic Clouds.

Gamma-ray observations provide a measurement of past supernova activity, especially within dense clouds where supernovae are essentially invisible. Supernovae produce a number of long-lived isotopes such as ^{26}Al and ^{60}Fe which can be used to trace out supernova activity in the Galaxy over the past few million years.

Cosmic rays, at least up to energies of order 10^{14} eV, are understood as being accelerated by shock waves created by exploding supernovae propagating into the interstellar medium. Measurement of the elemental composition of cosmic rays at such energies will test the limits of the supernova acceleration model and measurements of individual rare elements heavier than iron will distinguish between competing models of injection into these cosmic accelerators.

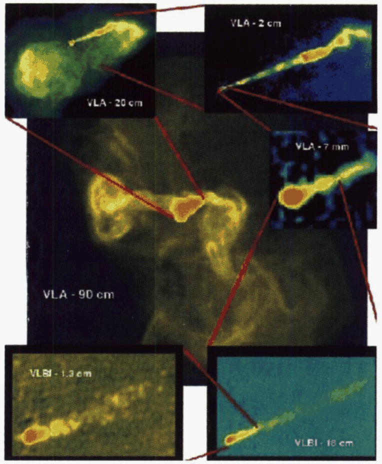
Direct sampling of the very local interstellar medium using a high speed probe sent outside the solar system would be particularly illuminating. Particle and field measurements on such a mission will reveal how stars and their winds contribute to the low energy cosmic rays in the Galaxy.

Through high spatial resolution observations, we also can explore the state of the interstellar material in external galaxies. This gives a global view that is impossible to obtain directly for our own Galaxy. In many cases, particularly starburst galaxies where recent galaxy-galaxy encounters have occurred, some of the interstellar gas has been heated to temperatures of several million degrees. The X-ray radiation from this gas can be used to map the amount and distribution t of heavy elements, which can tell us how uniform are the conditions within individual galaxies.

Many of the physical processes that underlie this campaign can also be observed at work in our own interplanetary medium. After all, the gas densities, temperatures, magnetic field strengths, cosmic ray energies, and so on span similar ranges. We can therefore regard the solar wind as it is launched by the sun, as it interacts with various planetary magnetospheres, and as it encounters the interstellar medium as a sort of laboratory where we can measure these effects with a detail that would be denied to us were we restricted to observations of remote cosmic sources. For this reason, there is a strong connection between this campaign and the scientific goals of the SEC theme.

3.4 Discover How Gas Flows in Disks and How Cosmic Jets are Formed

In recent years there has been abundant observational evidence, much of it garnered from space by SEU missions, to support the hypothesis that gas accretes onto compact objects (black holes, neutron stars, and white dwarfs) via accretion disks. For stellar objects, the gas derives from a normal, companion star. For the massive black holes in active galactic nuclei (AGN), the gaseous fuel comes from the central star cluster and gas that simply settles into the galactic nucleus. As this gas falls deeper into the gravitational potential well of the black hole, its energy is converted into heat through dissipa-



Energetic, collimated, relativistic outflow accompanying the black hole in M87—as seen in high-resolution radio maps. VLBI observations made from space could probe even finer scales.

tive stresses and then into observable ultraviolet, X-ray, and even gamma radiation.

It has also been discovered that cosmic jets are often formed as a natural concomitant of accretion disks. These collimated, bipolar outflows were first observed extensively from the ground using radio telescopes. However they are now regularly seen at optical, X-ray, and gamma-ray wavelengths as well and, in particular, from space. For example, the EGRET instrument on CGRO discovered that gamma-ray jets from active galactic nuclei were far brighter and more prominent than had generally been anticipated. The extension of Very Long Baseline Interferometry (VLBI) into space with the HALCA mission has enabled astronomers to see jets in finer detail than ever before. Understanding how these jets are made and what role they play in the accretion process is a major, unsolved problem. In particular, we hope to discover if they are launched and collimated by magnetic stresses or if the pressure of the intense radiation fields is responsible.

The most powerful active galactic nuclei are called quasars. These are so bright that they outshine the surrounding galaxy. While all galaxies may have passed through active phases, and thus may still harbor giant black holes at their centers, we know from observations that AGN were much more common at earlier epochs than at present. The high luminosities of AGN make it possible to observe these systems at very great distances, thereby providing fundamental information about the formation and early evolution of galaxies. X-ray and gamma-ray observations can probe the interior regions of accretion disks, those nearest the massive black holes. With high resolution spectral observations, X-ray emission line components have already been measured and allow us to probe the dynamics of gas flow close to black holes. A major challenge for the future is to extend this technique to many more objects and use it to measure the masses and spins of the central black holes.

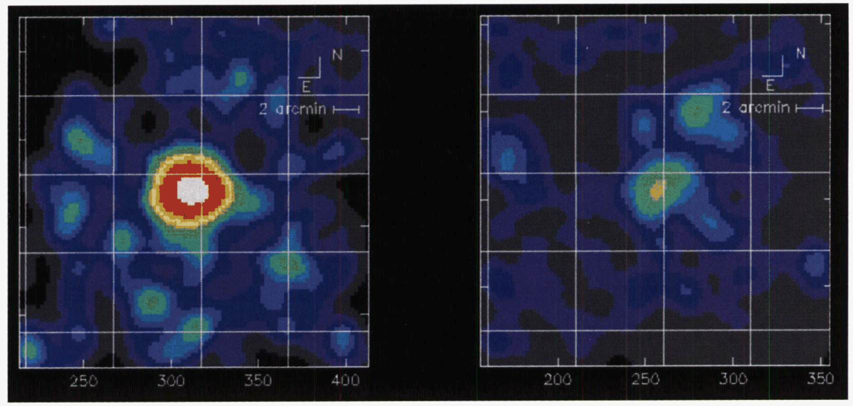
Observations of lower power (but much closer) galactic nuclei are also allowing us to see the outer parts of accretion disks and to understand how gaseous fuel is supplied to the central black hole. Recent VLBI experiments from the ground have detected intense water emission lines, amplified by a natural maser process, from several of these sources. This has enabled us to measure the mass of the central black hole with unprecedented accuracy. However, the full power of this technique will not be realized until there is a full-scale space VLBI capability.

There are many similarities between the stellar mass black holes and the very massive AGN black holes, despite the fact that their characteristic scales can differ by factors of more than a million. One of the most famous of the galactic sources, SS433, has jets extending for 10^{15} km in each direction, with material being ejected from the central source and moving in collimated beams at 26 percent the speed of light. In addition, some recently discovered Galactic binary sources show radio jets in which the apparent motion

of individual features appears to be faster than the formal speed of light. (This superluminal motion is just an optical illusion and there is no contradiction with the theory of relativity). Similar cosmic radio jets are often found associated with many active galaxies and trace the flow of the energy from the active galactic nucleus to the giant radio lobes observed at radii of several million light years. In many quasars, like 3C279, these jets are aimed in our direction, producing bright beams of gamma rays overwhelmingly more powerful and more rapidly variable than the radio jets. These gamma rays must originate from quite close to the source of the jet, almost certainly from an ultra-relativistic electron-positron plasma.

There are other approaches to understanding how accretion disks work. X-ray observations of Galactic binary X-ray sources often exhibit long trains of pulses, called quasi-periodic oscillations, with frequencies that can be higher than one kilohertz. These are telling us about the dynamics of the disk accretion process in much the same way that solar oscillations tell us about the structure of the sun. In addition, the observed X-ray emission from these sources shows dramatic changes in intensity on time scales that can be shorter than a second, and these wild variations are also reflected in the radio emission. This behavior has all the hallmarks of dynamical chaos, a generic feature of non-linear dynamical systems.

The goal of this campaign is to achieve an integrated understanding of disks and jets in all these different systems. This will require coordinated observations from radio to gamma-ray wavelengths. A VLBI network of radio/mm telescopes in space should reveal how jets are accelerated and collimated. Optical interferometric imaging, and, on larger scales, X-ray imaging, should elucidate the acceleration processes by which the relativistic electrons and positrons responsible for the non-thermal emission are created. Ultra-sensitive ultraviolet and X-ray spectroscopy is the unique tool for understanding the details of the accretion process by measuring directly



Fading X-ray afterglow from a gamma ray burst.

the range of velocities of gas with different temperatures; the cooler gas presumably traveling more slowly, the hotter gas orbiting a central black hole with a speed approaching the speed of light. Finally, sensitive gamma-ray observations, carried out in concert with radio VLBI studies, can probe both the jets and the disks closest to the central black hole.

3.5 Identify the Sources of Gamma-Ray Bursts and High Energy Cosmic Rays

As astrophysicists have pushed observations to higher and higher energy, they have discovered that their detectors are matched by cosmic sources. Nature is able to channel enormous powers into relatively few particles so that they have huge individual energies, far out of thermodynamic equilibrium. Some of these cosmic accelerators have been identified with specific sources; AGNs and pulsars are examples. However, some of Nature's most extreme accelerators are still unidentified. Two examples that stand out are the sources of cosmic gamma-ray bursts and of ultra-high-energy cosmic rays.

Cosmic gamma-ray bursts are intense flashes of gamma-rays which last from milliseconds to hundreds of seconds, during which they dominate the gamma-ray sky. The study of these mysterious objects has undergone a revolution in the last two years, spurred by the discovery of X-ray, optical, and radio counterparts, which fade away days to weeks after the event. The study of these "afterglows" has established that GRBs occur at great distances, and involve an enormous energy release (up to 1.9 $M_{\odot}c^2$ for one event if the emission was isotropic). The energy source of these enormous explosions, however, remains a mystery.

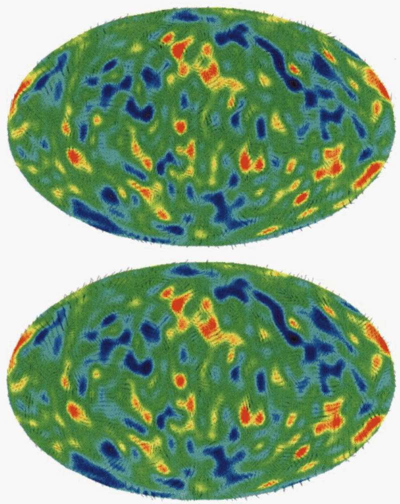
The most attractive current models for the GRB progenitor objects are the merger of two neutron stars, the merger of a neutron star and a black hole, or the collapse of a massive star. Observations of GRB afterglows and the underlying host galaxies have provided hints that some GRBs are directly associated with star forming regions, indicating that massive stars may be the progenitors of some types of GRBs. However, the evidence is still tentative, and only events of long duration have been studied. The BATSE experiment on CGRO has found that long and short duration events divide into two separated groups, and may therefore indicate that these arise from different energy sources. The upcoming HETE-2 satellite will provide accurate positions for both types of events, and future, high-quality follow-up will provide further clues.

Gamma-ray bursts have great potential for use as probes of the early Universe. If related to star formation, they are likely occurring to redshifts $z > 10$ where little other information exists on the subject. Independent of their origins, gamma ray bursts can produce optical and X-ray emission that is brighter than that of any other high redshift source. This provides new tools for measurement of the gas and dust content of early galaxies and the interstellar medium at high redshifts.

We have a reasonably good interpretation of how cosmic rays of low and intermediate energy are accelerated at shock fronts formed by solar flares and supernova explosions propagating though the interplanetary and interstellar media respectively. However, we do not understand the origin of cosmic rays of energies more than about 10^{14} eV. It is apparent that completely new accelerators are at work. They could be the radio pulsars; alternatively they might be a shock front formed where our galactic wind impacts the intergalactic medium. A major obstacle to identifying these sources is that we do not understand the composition of the particles. Are they protons or are they iron nuclei? Direct observation of the elemental composition of cosmic rays at energies 100–1000 will test the limits of the cosmic-ray acceleration model and locate their acceleration sites.

As we move to higher energies, the mystery deepens. In fact, we can measure the cosmic-ray spectrum all the way up to $\sim 3 \times 10^{20}$ eV, where individual particles have the energy of a well-hit baseball! About the only conceivable sources for these particles are galactic nuclei, the giant extragalactic double radio sources or the same mysterious sources as the gamma-ray bursts themselves. Here the problem is that the detection rate of these particles is so low that we see too few of them to describe their properties well. Instruments capable of monitoring large areas of the Earth's atmosphere for the showers that these rare particles produce will establish the energy spectrum of these highest energy cosmic rays and are likely to determine directions to these sources.

However, this campaign is more general than these two examples. Whenever we push back the frontiers of cosmic discovery, we reveal the unexpected. As there are still extremes to be explored for the first time, we are confident that there are more surprising discoveries like these waiting to be made.



Theoretical calculation of the polarization signature (arrows) imposed on the CMB due to a predicted gravitational wave background.

3.6 Measure How Strong Gravity Operates Near Black Holes and How It Affects the Early Universe

Over the past decade, Einstein's general theory of relativity, once the exclusive property of the mathematical physicist, has been spectacularly corroborated and has become an everyday tool of the astrophysicist. Black holes appear to be commonplace in active galactic nuclei and occasionally present in binary stellar systems, and their properties are peculiarly relativistic. Even neutron stars exhibit special signatures of general relativistic effects.

The strong gravitational fields around black holes may be probed by observing the radiation emitted by accreting gas. As we have described, this is expected to orbit in a disk before eventually being swallowed by the hole. The mass of the hole can be found if the velocity of the orbiting gas (or stars) at a known distance from the hole can be measured. Observations with the Hubble Space Telescope have allowed the masses of the supermassive black holes at the centers of galaxies to be determined using this method. However, detecting the distortions of spacetime produced by the black hole, and hence checking Einstein's theory of general relativity, requires observations much closer to the hole just outside its event horizon (the boundary of the region from within which light cannot escape from the hole). Emission lines from gaseous iron orbiting just outside the event horizon of supermassive black holes have recently been observed by ASCA. These lines have the widths expected for gas moving at speeds close to that of light, but the observations do not have the sensitivity to check the theory of general relativity. Better observations of these X-ray lines can confirm or refute Einstein's theory and also tell whether the black hole is spinning (the mass and spin provide a complete description of a black hole in an astrophysical setting). Although theories of black holes predict they should have spin, current telescopes are too limited to measure this vital property, which may be responsible for the powerful radio jets which propagate millions of light years from the centers of radio galaxies.

In addition to the existence of black holes, general relativity also predicts that gravitational waves, propagating ripples in the curvature of spacetime, are transverse (like electromagnetic waves), have two independent polarization states, and propagate at the speed of light. Unlike electromagnetic waves, however, these tensor waves are extremely weak. This weakness has two consequences. First, it makes them experimentally very difficult to measure. Gravitational waves can be detected interferometrically by observing the change in distance between separated test masses. The fractional changes predicted to be observed near Earth from likely sources of gravitational waves are of the order of 10^{-20} or smaller in the low frequency (10^{-5}–10^{-1} Hz) band accessible with space experiments. Second,

once generated, gravitational waves interact so weakly with matter that they propagate with negligible scattering or absorption. This means that, unlike electromagnetic waves, gravitational waves preserve information about the strong-gravity, high-velocity regions where they are generated, unconfused by subsequent scattering or absorption in their propagation.

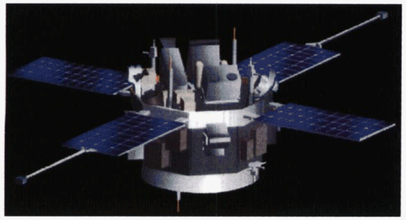
Gravitational waves are interesting both as probes of the fundamental nature of gravity and for the unique astronomical information encoded in their waveforms. Detailed studies of cosmic gravitational waves would provide strong-field tests of general relativity as well as astronomical information unlikely to be obtained in any other way. Currently the most promising sources of gravitational waves observable from space are perhaps merging massive black holes in active galactic nuclei at clearly detectable levels. Somewhat weaker, but more frequent bursts are expected to be produced when individual stars are captured by massive black holes and selected galactic binary stars should produce promising periodic sources. More speculatively, there may be a continuous background of gravitational radiation from the very early Universe. Detection and subsequent detailed study of these gravitational waves will open a new window for observational astronomy, giving information fundamentally different from that contained in photons.

One of the most exciting long term goals of astronomical imaging is to achieve an angular resolution capable of resolving a supermassive black hole in the nucleus of a nearby galaxy, for example the famous radio galaxy Centaurus A, where an angular resolution of better than 1 μarcsec would be necessary. Unfortunately, it will not be possible to achieve this fine a resolution using radio telescopes because the interstellar medium has its own "seeing" and blurs images just like our own atmosphere at optical wavelengths. However, an array of very long baseline (more than a million km) orbiting millimeter or submillimeter telescopes might be able to achieve this goal. Achieving this imaging capability at optical wavelengths is also one of the goals of the ASOPS theme. Although technically difficult, X-ray interferometry will offer yet another window on this problem.

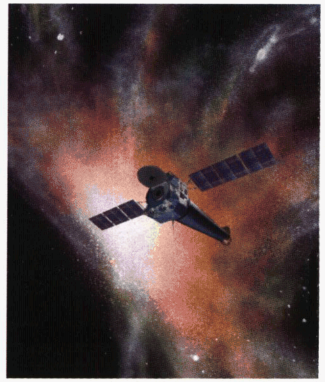
As astrophysical questions about strong gravity and black holes are answered by the SEU theme missions, they will be replaced with new and deeper questions. We can hope that, by the end of the period covered by this, the first-generation spaceborne detector will have observed gravity waves from thousands of Galactic binaries, detected or constrained a background of low-frequency gravity waves from the Big Bang, and probably have observed low frequency waves from massive black holes. This detector will have given the first direct observational evidence on the formation, growth, and space density of massive black holes in the mass range 10^2–10^6 solar masses. Thereafter, combined electromagnetic and higher sensitivity gravitational wave observations will probably be needed to give definitive information on the conditions under which massive black holes form and grow. Did they form directly from gas and dust or did they grow initially from collisions of stars? Were they present in pre-galactic structures or did they form at later times? Finally, did their existence play a significant role in how galaxies formed in the first place?

4 The Current SEU Program

The current SEU program is a mix of operational missions and those awaiting completion and launch. It has been characterized by a high success rate, both in terms of technical performance and in terms of fulfilling, and usually exceeding, science goals. In recent years, it has also been especially responsive to the call to make mis-



The Advanced Cosmic Explorer is measuring the composition of energetic nuclei from the Sun and Galaxy.



The recently launched Chandra Great Observatory is probing conditions near the event horizons of black holes, dark matter in galaxies and galaxy clusters, as well as other energetic phenomena.

sions faster, better, and cheaper. The major discoveries of the current missions have attracted exceptional interest in the media and with the general public.

Recent highlights of the program include the successful launch and operation of NASA's Great Observatory, the Chandra X-ray Observatory, and of the SWAS Small Explorer mission. In addition, U.S. participation in ESA's Cornerstone missions, FIRST and Planck, has been approved and these collaborative efforts are underway. Finally, the GLAST mission, identified as a New Start in the previous SEU Strategic Plan, has completed technology development, and instrument proposals have been solicited. We anticipate the new start for this mission in 2002.

Below we describe major SEU missions and their scientific objectives.

Missions in Operation

The Advanced Composition Explorer. The Advanced Cosmic Explorer (ACE) measures the composition of energetic nuclei from the Sun and the Galaxy, including solar wind, solar energetic particles, and anomalous and galactic cosmic rays. ACE was successfully launched on August 25, 1997, and is currently taking data on orbit at the L1 Lagrange point (a position of Earth-Sun gravitational equilibrium about 1.5 million km from Earth and 148 million km from the Sun). ACE's nine scientific instruments measure the elemental and isotopic composition nuclei from H to Zn ($1 \leq Z \leq 30$) over a broad dynamic range (~100 eV/nucleon to ~500 MeV/nucleon), including material from the solar corona, from the nearby interstellar medium, and from galactic cosmic-ray sources. The scientific objectives include comparisons of the isotopic composition of solar and galactic material, studies of acceleration processes on scales ranging from interplanetary shocks to supernova shocks, and studies of cosmic-ray transport in the Galaxy and the heliosphere.

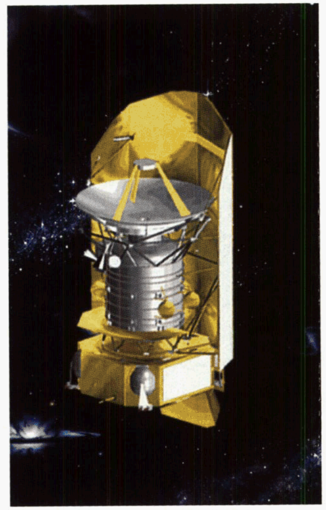
***Chandra* X-ray Observatory.** With 1 arcsecond imaging capability and energy resolution ($E/\Delta E$) as high as 10^3, Chandra provides high resolution X-ray images and spectra for all classes of celestial objects ranging from planets and stars to clusters of galaxies and quasars. Chandra probes production of heavy elements in supernova explosions, conditions near the event horizon of black holes, dark matter in galactic halos and clusters of galaxies, and other phenomena associated with the hot and energetic aspects of our Universe. Chandra was launched on July 23, 1999, and the first light X-ray image of the supernova remnant Cas A is shown on the cover of this document. At the time this Plan was written, the spectacular imaging and spectroscopic performance of the observatory had already been demonstrated on multiple cosmic sources.

Missions Planned or Under Development

ASTRO-E. The ASTRO-E Observatory, a joint program between NASA and the Japanese Space Agency, will provide high-resolution spectroscopic capability with modest spatial resolution. The observatory consists of a central telescope combined with a microcalorimeter array (2 × 16 pixels), four conical mirror X-ray telescopes with CCD detectors and with better angular resolution than ASCA (2'), and a collimated 10–700 keV detector. The first two years provide GOs with 50% of the observing time. The cryogen for the microcalorimeter is expected to be depleted by this time. After the first two years, the time is 15% US, 25% US–Japanese.

FIRST. One of the last regions of the electromagnetic spectrum yet to have a major space observatory devoted to its study is the far infrared/submillimeter. The major extragalactic sources in this wavelength region are dusty galaxies from which almost no visible light escapes. Such galaxies, discovered by the Infrared Astronomical Satellite (IRAS) nearly two decades ago, have very high rates of star formation. The recent detection of the far infrared background by the Cosmic Background Explorer (COBE), and its partial resolution into discrete sources by the Infrared Space Observatory (ISO) at 170 μm and by observations from the ground at longer wavelengths, underscore the importance of such galaxies to our understanding of the origins of galaxies and stars, one of fundamental questions driving NASA's Strategic Plan.

With photometric and spectroscopic capability in the range 80–670 μm, FIRST is designed to detect these galaxies out to large cosmological distances, where they may play a dominant role in the star formation history of the Universe. In addition, it will be able to detect regular spiral galaxies like our own, which radiate almost half their bolometric luminosity in the far infrared, out to intermediate redshifts.

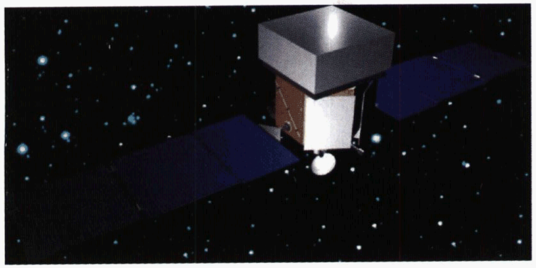


FIRST will detect dusty galaxies to large cosmological distances, where they may play a dominant role in the star formation history of the Universe.

The major Galactic sources in the infrared/submillimeter spectral region are dense molecular clouds where stars are forming, protostars, regions of molecule formation in the interstellar medium, and disks around stars. FIRST will study these sources, major components of the cycles in which matter, energy, and magnetic field are exchanged between stars and the interstellar medium, both with imaging arrays and through high dispersion spectroscopy.

FIRST is a cornerstone mission of the European Space Agency. It will be launched on an Ariane 5 rocket together with Planck in 2007, and will operate (separately from Planck) at the L2 Lagrange point. NASA's contributions to FIRST include the 3.5 m telescope as well as major components of two of the three instruments, the Spectral and Photometric Imaging Receiver (SPIRE) and the Heterodyne Instrument for FIRST (HIFI).

Gamma-ray Large Area Space Telescope (GLAST). The revolution in our understanding of the high-energy universe will continue with the Gamma-Ray Large Area Space Telescope (GLAST).



GLAST will probe fundamental physics of blazar AGN and pulsars.

The latest in a series of pair production telescopes to explore particle acceleration in extreme environments, GLAST will operate over the energy range from 20 MeV–300 GeV. GLAST provides a very large field-of-view (2 sr) and large effective area (8000 cm^2) along with enhanced spatial resolution as compared to the CGRO/EGRET instrument. These advances will result in limiting sensitivities a factor of 30 or more better than EGRET for an initial two-year survey.

GLAST will contribute to our understanding of a wide variety of astrophysical environments. Following the success of the CGRO/EGRET instrument, GLAST will provide more and better data on the fundamental physics of blazar AGN and probe the isotropic gamma-ray background radiation to unprecedented levels. Spectral studies of blazar emission will allow measurement of the infrared background light through pair production with GeV photons. Breakthroughs in the study of pulsar emission and the nature of the unidentified gamma-ray sources will be another major facet of GLAST science. Further studies will include mapping of diffuse emission in nearby galaxies and from galactic molecular clouds, solar flare studies, and a unique view of the high-energy emission from gamma-ray bursts.

The GLAST mission is scheduled for a new start in 2002 with an anticipated launch in 2005. Technology development is well underway with an open competition for the final instrument design and a final instrument selection in January 2000. The likely competing designs are based upon silicon strip detectors and scintillating fiber technology. Current plans are for a Delta 7920 launch into a 28.5 deg inclination circular orbit at an altitude of 550 km. A five-year mission life is assumed (goal of 10 years) with the first year dedicated to an all-sky survey followed by pointed observations.

The Microwave Anisotropy Probe (MAP). The COBE satellite provided the first major step forward in space-based cosmology. COBE verified beyond all reasonable doubt that the cosmic microwave background (CMB) had a cosmological origin and detected the tiny primordial perturbations from which large-scale structure in the present-day Universe grew. The next obvious step in this endeavor is to measure these fluctuations with greater sensitivity and on smaller angular scales. Such precise high-resolution maps of the CMB can be used to determine the geometry of the Universe, the density of baryons, dark matter, and vacuum energy in the Universe, and the precise initial conditions for structure formation. Moreover, the CMB may also be capable of determining the physics in the very early Universe (e.g., inflation) responsible for producing primordial perturbations.

The next major step will be taken by the Microwave Anisotropy Probe (MAP), which will be launched at the end of 2000. MAP will make differential measurements of the CMB temperature on the full sky using pseudo-correlation radiometers coupled to back-to-back 1.4×1.6 meter primary Gregorian reflectors. Five frequency bands from 22 GHz to 90 GHz will allow emission from the Galaxy to be modeled and removed. The resulting map of the sky should allow an unambiguous determination of the geometry of the Universe and of the spectrum and nature of primordial perturbations. MAP will also provide unique information that will help determine the baryon density, Hubble constant, dark-matter density, and cosmological constant.

Planck. ESA's Planck mission will represent the third step in measuring the CMB from space, with angular resolution and sensitivity better by factors of more than 2 and 5 compared to MAP, respectively. Moreover, with frequency bands from 30 GHz to 857 GHz, Planck will provide maximum discrimination between the background radiation and foreground sources. The improved sensitivity will allow the polarization (as well as the temperature) of the CMB to be mapped to the cosmic-variance limit for the first time. With such improvements, Planck will allow precision measurements of the dark-matter, baryon, and vacuum-energy densities, Hubble constant, and thus forecast the ultimate fate of the Universe. It will determine precisely the primordial spectrum of perturbations over three orders of magnitude in length scale. The polarization capabilities will allow new and unique tests of inflation that may conceivably determine the energy scale of inflation. Planck will be launched with FIRST in 2007, and (like MAP) operate at the L2 Lagrange point. NASA's contributions to Planck include a vibrationless hydrogen sorption cooler system, bolometers, and HEMT amplifiers. The US leads the world in all of these technologies, in large part due to past and continuing NASA support.

XMM. The X-Ray Multi-Mirror Mission is a joint ESA/NASA mission that will provide high-sensitivity imaging, as well spectroscopic capability in the X-ray band. XMM consists of three telescopes with about 10 arcsecond image quality, CCD and PN-CCD detectors, with two of the telescopes equipped with objective gratings. An optical monitor telescope is also included to provide optical and ultraviolet photometry and low resolution spectroscopy of the observed sources. While the telescope resolution is not as good, the overall effective area of the X-ray mirror system is about 10 times that of the Chandra Observatory. The spectral resolution is about 300 at best compared to 1000 for the Chandra Observatory. After an initial calibration period of about two months, the observing time eventually becomes available to guest observers around the world over the first two years.

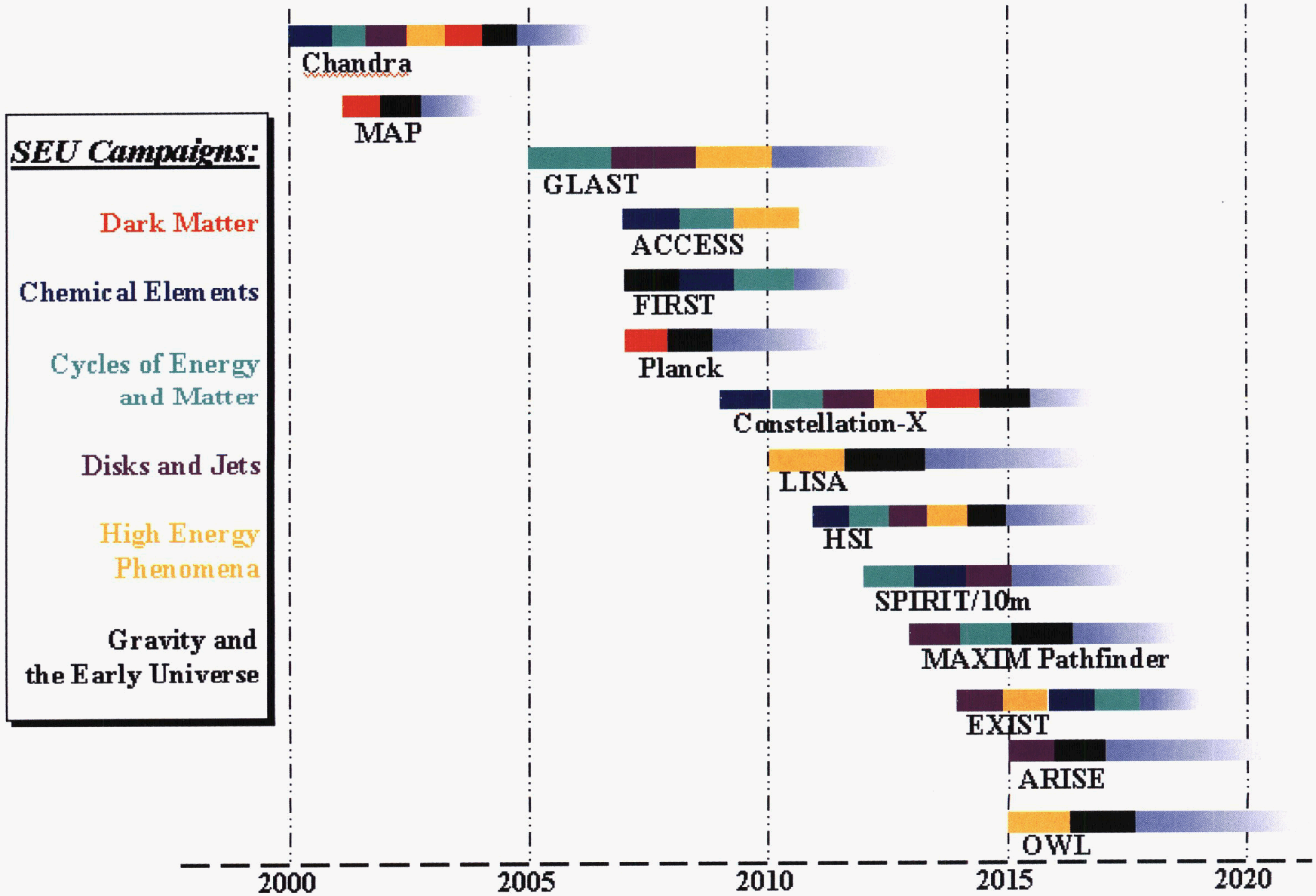
5 Mission Portfolio

SEUS has carefully reviewed the 1997 SEU Roadmap ("The Evolving Universe, Roadmap 2000–2020") and found that our current goals agree remarkably well with that document, strengthened by impressive progress on many of the scientific problems since the time that previous study was completed. We therefore assume as a starting point in our new deliberations that the program described there has continued to make good forward progress. In the area of major projects, we assume that the Chandra X-ray Observatory will be mature and producing vigorous science, and that GLAST, currently having completed technology studies and the subject of a current Announcement of Opportunity, will be on-orbit and also producing exciting results. Further, together with our international colleagues, we will be well on the way to seeing the launch of FIRST and Planck. A vigorous Explorer program, at least comparable to and hopefully in excess of the current effort, will also be mandatory to move the important SEU problems forward.

Building on this assumed base, we have examined major projects in the SEU area, and divided them into three categories: missions ready for new-start status in the near term (next five years), candidates for midterm new starts (2008–2013), and "vision missions" (2014 and beyond).

Projects in the first category have their scientific goals and technical approach defined in great detail, with varying levels of technology development needed to actually enter Phase C/D. Our community is ready and eager to press forward with these programs, which will tackle and solve the major outstanding questions in the SEU

Complementary SEU Missions Target the Campaigns with Increasing Technical Sophistication and Scientific Insight



theme. These missions will be the core of SEU science in the new millennium.

Projects in the midterm category involve well-delineated scientific problems and technical approaches, could be ready for new start status in 2008–2013, but require substantial technology development, beyond the current state of the art, to move forward. They all appear to be technically feasible, but their rate of progress will depend upon investment of technology funds. Such investment not only enables these specific missions, but often applies to other NASA programs, and often also to unrelated technologies, sometimes far outside of space science.

The "vision missions" are where we stretch our imagination. The scientific problem to be solved is evident, but the technology required to do so is only loosely defined. Considerable development will be needed to bring these to fruition, and indeed some may not prove feasible at reasonable cost. Again the needed technologies often span multiple NASA programs. The sooner we begin investment in these problems, even at a relatively modest level, the sooner we can plan a cogent program for the end of the interval under consideration, near 2020.

5.1 The Strategic Plan: 2003–2007

SEUS has identified three very clear, top-priority near-term science objectives together with missions to accomplish these goals. The three problems span a diverse range of subdisciplines, of observational technique, of timescales, and of cost, and are thus complementary, forming a coherent core program for the SEU theme. We reaffirm the exceptionally high priority of broadband, high-throughput X-ray spectroscopy to be accomplished by the Constellation-X mission, the only remaining mission from the previous Strategic Plan yet to obtain new start status. With continued investment of modest technology funds, this mission can be ready for a new start near the beginning of the window considered for the near-term major programs, and will be the natural transition from the groundwork laid by Chandra, XMM, and ASTRO-E.

In an entirely different but surely equally exciting arena, we enthusiastically recommend a sensitive search for gravitational radiation at far lower frequencies than feasible from the ground, with the Laser Interferometer Space Antenna (LISA). Our European colleagues are also enthusiastic about this science, and thus this ambitious project may be well-suited for an international collaboration, as has been so successful on other recent major programs in space science. While there appear to be no insurmountable technical barriers to this mission, LISA requires some challenging technology development, preferably supported in part by a space-borne demonstration. This program is thus complementary to Constellation-X, as its natural timescale places it near the end of the near-term new-start window.

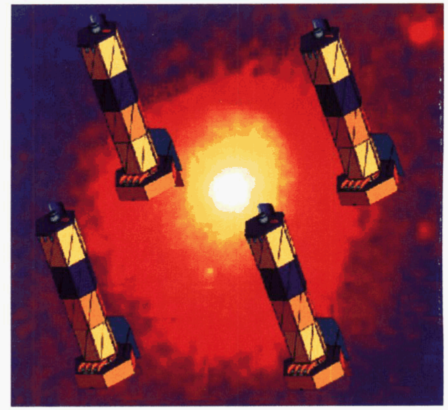
Finally, we describe an exciting opportunity to solve one of the outstanding problems in cosmic-ray physics with the Advanced Cosmic Ray Composition Experiment for Space Station (ACCESS). ACCESS employs an approach uniquely suited for the International Space Station (ISS) as a host platform. Although its cost is moderate compared with typical OSS new starts, we propose it here, as its schedule, driven by that of ISS and its payloads, makes it unsuitable for the Explorer program.

The Constellation X-ray Mission. Optical astronomy transitioned into astrophysics more than a half-century ago when it became routinely possible to obtain spectra with resolution of $\lambda/\Delta\lambda \sim 3000$. Velocities of hundreds of kilometers per second, ubiquitous in both galactic and extragalactic objects in the Universe, then became measurable, and key multiplets of common nuclei could be resolved to yield quantitative plasma diagnostics. As X-ray astronomy approaches its half-century anniversary, however, imaging capabilities have far outrun spectroscopy, and X-ray astronomers by at least this criterion have not yet entered the routine spectroscopic era. There are indeed a handful of X-ray spectra of this high resolution currently available, and in the next decade we can expect Chandra, XMM, and ASTRO-E to raise this inventory to at least several dozen objects of each astrophysical class. This will be a fabulous harvest, teaching us how to use X-ray spectra for quantitative analysis, just as the optical astronomer learned decades earlier. But just as the optical astronomer would hardly be satisfied being confined spectroscopically to naked eye stars, X-ray astronomy can hardly flourish when it is confined to the very brightest few dozen examples of each class, leaving us unable to judge neither the physical diversity of objects, nor their evolution with cosmic time.

Constellation-X will provide a hundred-fold increase in sensitivity over the high resolution spectroscopy capabilities of current missions such as Chandra, XMM, and ASTRO-E. Constellation-X is the X-ray astronomy equivalent of large ground-based optical telescopes such as the Keck and the VLT, complementing the high spatial resolution capabilities of Chandra. Thus the targets of Constellation-X are not speculative, but rather will be largely well-catalogued by the current generation of sensitive imaging missions.

Constellation-X will address questions concerning the extremes of gravity and the evolution of the Universe. X-ray observations of

Constellation-X will provide a hundred-fold increase in sensitivity over the high resolution spectroscopy capabilities of current missions, enabling it to address questions concerning the extremes of gravity and the evolution of the Universe.



broadened iron emission lines in Active Galactic Nuclei will measure black hole masses and spins, exploiting general relativistic effects occurring in the strong gravity limit. Constellation-X will trace black hole evolution with cosmic time and provide new insight into the contribution of accretion processes to the total energy output of the Universe. By looking across a broad range of redshifts, Constellation-X will reveal the formation epoch of clusters of galaxies and relate the observations to current models of galaxy formation. Present inventories indicate that many baryons predicted by Big Bang nucleosynthesis and subsequent stellar processing seem to be missing, and Constellation-X will search for them—for example, in a hot metal-enriched intergalactic medium. Constellation-X will identify large numbers of X-ray spectral lines in stellar coronae, supernova remnants, and the interstellar medium providing essential information on chemical enrichment processes as well as detailed measures of plasma temperature, pressure, and density over a wide range of astrophysical settings.

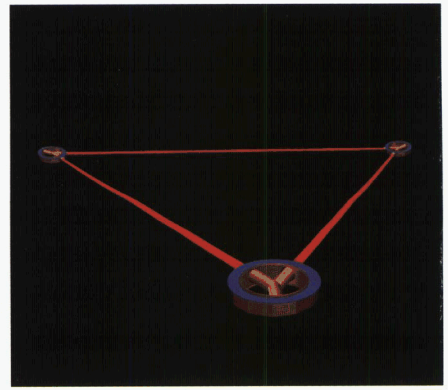
Constellation-X was included in the 1997 OSS Strategic Plan as a candidate New Start for 2004, requiring significant technology in-

vestment in a number of areas. Notwithstanding limited funding to date, very substantial progress has been made in several key areas including light-weight X-ray mirrors, improved energy resolution of X-ray microcalorimeters, multi-layer depositions for hard X-ray telescopes, CZT detectors for hard X-rays, and the overall multi-satellite approach to the mission. With additional technology investments to sustain this rapid progress over the next few years, Constellation-X will be ready for a new start in 2005.

The Laser Interferometer Space Antenna (LISA). One of the last non-electromagnetic channels to be opened is that of gravitational radiation. Gravitational waves are propagating, polarized gravitational fields which can be detected by measuring the change they cause in the distance between separated test masses. Gravitational waves are generated at detectable levels only by massive astrophysical sources undergoing violent dynamics. Once generated, the waves propagate unaffected by scattering or absorption due to intervening matter. This makes them difficult to detect, but it also means that they give information on strong gravity, and high-velocity astrophysical regions not obtainable by other means. Although waveforms have not yet been directly detected, there is clear evidence that gravitational radiation exists. The observed orbital decay of the radio pulsar PSR 1913+16 is precisely consistent with the predicted energy loss due to gravitational radiation.

There are several ground-based projects to detect gravitational waves, including the U.S. Laser Interferometer Gravitational Wave Observatory (LIGO), which will be sensitive to waves with ~10 Hz to kHz frequencies. Such waves are produced by objects such as supernovae, coalescing neutron stars, and coalescing stellar mass black holes. Another very interesting spectral range is the millihertz region (signal periods of minutes to hours). Here the strongest prototypical source might be two coalescing massive black holes in an AGN. Because of seismic and gravity gradient noise backgrounds, it is impossible to measure these low-frequency waves from the ground. LISA ("Laser Interferometer Space Antenna") is a spaceborne gravitational-wave observatory which will be sensitive to these lower frequency waves. It will consist of three spacecraft orbiting the Sun in an equilateral triangle formation with 5×10^6 km sides. The center of the triangle is in the ecliptic, 1 AU from the sun, trailing about 20° behind the Earth. Using laser interferometry in the relatively quiet space environment, LISA will detect low-frequency gravitational waves by monitoring tiny distance changes between proof masses within each spacecraft. LISA will be sensitive in the frequency range 0.1 mHz to 1 Hz (i.e., much lower in frequency than LIGO). LISA will thus complement ground-based gravitational-wave observatories; the huge difference in frequencies means that there is no overlap between the expected sources in the low (LISA) and high (LIGO) frequency bands.

LISA will detect gravitational radiation in a region of the spectrum not accessible from the ground—probing high-velocity astrophysical regions and providing fundamental information on strong gravity.



LISA's scientific objectives are:

- To make the first observations of gravitational waves from supermassive black holes in galactic nuclei.

- To observe gravitational radiation from compact stars scattered into capture orbits around supermassive black holes.
- To take a census of all short-period compact galactic binaries in our Galaxy.
- To search for a gravitational wave background from the early Universe and to search for unexpected sources of gravitational waves.

For periodic sources, LISA will achieve angular resolution of about 0.5° (strong sources, determined from the amplitude and phase modulation of the signal as the LISA array orbits the sun) and strain sensitivity with one year integration time, of ~10–23 at frequencies of a few mHz.

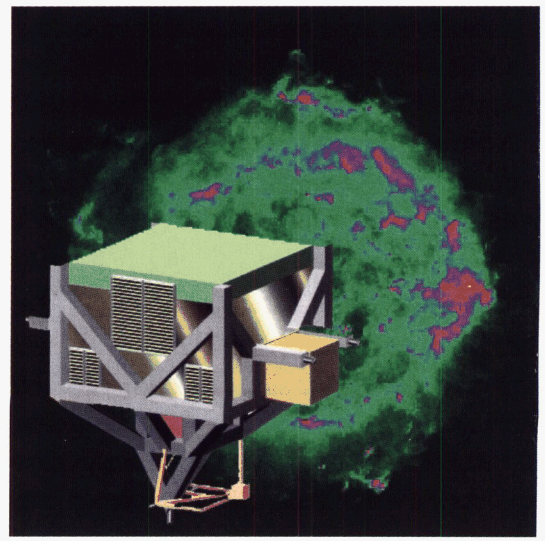
Three key technologies are needed to make LISA a reality. First, inertial sensors, with proof masses isolated from non-gravitational forces, must be employed. Second, micro-thrusters to keep each spacecraft centered on its proof mass are required. Third, laser metrology to measure sub-picometer changes in distance between widely separated proof masses is needed.

The LISA concept is the product of a large international collaboration. LISA will be a cooperative project of NASA and ESA. The LISA concept was strongly endorsed in the 1990 NASA Report of the Ad Hoc Committee on Gravitation Physics, in the joint NAS/NRC (1988) report on Space Science in the Twenty First Century: Imperatives of the Decades 1995–2015, and in ESA reports concerning their future program.

The Advanced Cosmic-Ray Composition Experiment for the Space Station (ACCESS). Cosmic rays are an important part of the dynamics and structure of our Galaxy. Their impact is largely hidden from us, since the magnetic fields and shock structures with which they interact are not directly visible to us, so we must study them by detailed measurements on the arriving particles themselves. The population of cosmic rays contains all of the known long-lived charged particles and has an average energy density which is similar to that of the magnetic fields and photons in our Galaxy. The overall distribution of cosmic-ray energies is remarkable in that it is almost a constant power law over at least 13 decades in energy and 31 decades in flux. The present view of the origin of most of these particles is stochastic acceleration of particles at the shock fronts produced by supernovae. Although recent X-ray and high energy gamma-ray observations have shown non-thermal concentrations of electrons near such shocks, the strongest argument for these ideas on the origin of the bulk of cosmic rays remain simple: only supernovae can supply the enormous power needed to sustain the population of cosmic rays.

ACCESS (Advanced Cosmic Ray Composition Experiment for the Space Station) is an instrument designed to directly explore the

ACCESS will directly explore the origin of energetic cosmic rays. It is believed that only supernovae can supply the enormous power needed to sustain this population of energetic particles.



connection of cosmic rays with supernovae. A small steepening, or "knee," in the slope of the power law energy spectrum of cosmic rays near 10^{15} eV is thought to be associated with the maximum possible energies achievable by direct supernova shock acceleration of cosmic rays. ACCESS has a large enough collecting power to measure directly the particles near these energies, which were previously only detected by the air showers they produced in the Earth's atmosphere. The direct measurements can provide the crucial missing information on how the fluxes of each type of cosmic-ray nucleus act at high energy. This is not possible with air showers. This gives an essential added dimension of enormous value, similar to that added by spectroscopy in visible light measurements.

The individual elemental spectra can be used to directly determine the source spectra of the cosmic-ray nuclei. The simplest theory of shock acceleration expects these all to be similar power-law forms which seem inconsistent with present measurements. ACCESS can study these spectra with unprecedented accuracy over more than four decades in energy in a single instrument. There are known to be features associated with atomic energy scales in the elemental composition of the cosmic-ray sources relative to Galactic material. ACCESS can determine if these features persist to the highest energies. ACCESS can directly measure the cosmic-ray energy spectra into the "knee" region. A direct study can be made of the characteristic signatures of the upper limits of supernova shock acceleration.

These individual fluxes can also be used to reconstruct the history of cosmic rays in our Galaxy. We already know that at lower energies, cosmic rays escape more easily from the plane of the Galaxy as their energy increases. We also know this kind of behavior cannot continue to the high energies of the "knee" region since large anisotropies in arrival direction would be produced which are not observed. ACCESS will have sensitive enough detectors to discover how this transition occurs.

To collect enough of the very high-energy cosmic rays, ACCESS must be a very large instrument, with several square meters effective collecting area. To provide an energy estimate for lighter cosmic rays, ACCESS must also contain a calorimeter. These features combine to make ACCESS by necessity a large and heavy instrument for spaceflight. However, the lack of accurate pointing requirements make this instrument a unique match to the experimental facilities of the International Space Station (ISS), where the Space Shuttle can easily lift massive payloads to the attachment points. ACCESS is designed for a zenith-pointed site on ISS, consisting of the combination of a large area transition radiation detector with a hadronic calorimeter. It is designed to measure individual elements over the range $1 < Z < 28$ up to energies of $\sim 10^{15}$ eV.

5.2 Midterm Missions: 2008–2013

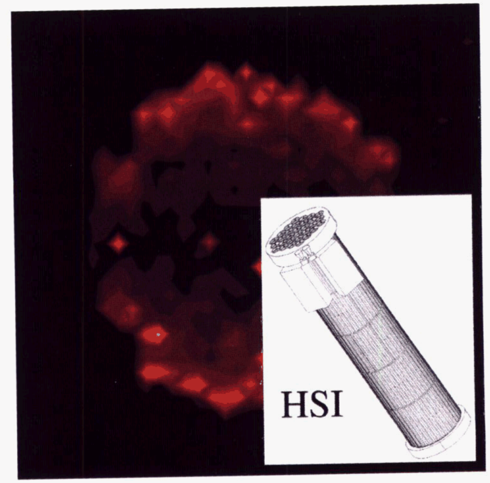
The selection and prioritization of candidate new start missions for the midterm (2008–2013) poses special challenges. These are missions whose precise progress towards launch will depend on the rate of development of cutting-edge technologies, which may be difficult to accurately predict, and whose scientific goals may evolve as new, relevant results arrive over the next decade. We have identified a set of six exciting scientific problems and missions to address them, and divided these into two groups of three.

The first group has our highest priority recommendation in each of three subdisciplines: X-ray, gamma-ray, and far IR astronomy. These are the missions that will be the "seed corn" of each of these fields—the ambitious goals, to tackle the most basic and important science, that keeps each fields vigorous and moving forward through the second decade of the millennium. These missions, described below in order of increasing wavelength, are a High-resolution Spectroscopic Imager (HSI) for gamma-ray astronomy, a MicroArcsecond

X-ray Imaging Mission (MAXIM) technology pathfinder, and a bold program in large far-infrared optics, applicable to both large (10 m class) filled aperture arrays as well as 30 m baseline class interferometers.

The second group of high priority midterm recommendations includes three further missions which each tackle essential scientific problems. The Orbiting Wide Angle Light Collectors (OWL) will provide dramatic new capabilities in cosmic rays; the Energetic X-ray Imaging Survey Telescope (EXIST) will complete the first all-sky map of the celestial sphere in hard X-rays; and the Advanced Radio Interferometry Between Space and Earth (ARISE) will probe the radio sky with unprecedented angular resolution.

The HSI will address fundamental questions on the origin of heavy elements, and black holes, through sensitive hard X-ray measurements.

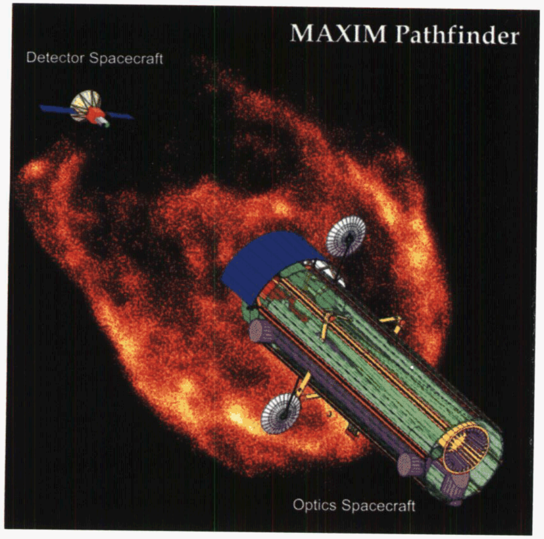


5.2.1 Highest Priority Missions

The High Resolution Spectroscopy Mission (HSI). An exciting new approach to nucleosynthesis studies is embodied in the High Resolution Spectral Imager (HSI). Many important nucleosynthetic lines lie in the hard X-ray range including ^{44}Ti (68, 78 keV), ^{57}Co (122 keV), and ^{56}Ni (158 keV). Sensitive spectroscopic and imaging observations of these lines in young supernova remnants, and studies of the time-evolution of prompt lines emitted in recent explosions, provide diagnostics on the production and distribution of heavy elements, and on the explosion mechanism itself. HSI is a hard X-ray focusing mission operating in the 1–200 keV energy range. Its sensitivity for detecting hard X-ray lines is 10^{-7} photons cm^{-2}s^{-1}, a factor of 40 better than that of the upcoming INTEGRAL mission. HSI is sensitive enough to detect lines from SN 1987A, and Type 1 supernovae in the Virgo cluster of galaxies and beyond. In addition to the line science, HSI will provide sensitive spectral studies of active galaxies, measurements of magnetic field strengths in galaxy clusters, and a new view of accreting neutron star and black hole binaries in our galaxy as well as the local group of galaxies.

Development of HSI depends upon improvements in hard X-ray focusing technology by extending multilayer optics to higher energies. Germanium detectors will be used at the focus to provide high resolution spectroscopy. The basic required technologies for HSI are expected easily to be ready in time for a new start in 2008 and launch in 2010. HSI is at the small end of the Intermediate mission class.

X-ray Interferometry Pathfinder. A central part of the long range "Grand Challenge" proposed by the XAPWG is direct imaging of the event horizon of a black hole. This will require ~0.1 microarcsecond resolution, or almost seven orders of magnitude better than Chandra, which is itself about a one order of magnitude improvement over Einstein. This clearly cannot be accomplished in one step. We propose to focus current efforts on a mid-term mission to serve as a pathfinder toward this ultimate goal. The strawman configuration for this is a working interferometer with 100 μas resolution and about 100 cm^2 effective area. This would itself be a tre-



The MAXIM pathfinder will test visionary technology as well as carry out important scientific objectives.

mendous advance in X-ray resolving power and would have substantial scientific capability of its own.

At 100 μas, one can:

- examine stellar plasma interactions in close binary systems
- study the structure of the X-ray producing shocks in O and B star winds
- look for wind-disk interactions in preordain sequence stars
- image the active coronae of nearby stars with 100 picture elements, allowing the morphology of the corona to be determined
- detect and resolve an accretion disk around the massive black hole at the center of the Milky Way
- image jets, outflows, and broad-line regions in bright AGN
- map the center of cooling flows in clusters of galaxies, locate and resolve any star formation regions

All of these goals should be achievable with 100 cm^2 effective area.

High-Resolution Far Infrared Mission. The behavior of interstellar and circumstellar gas and dust lies at the heart of many fundamental questions about the Universe, from the formation of galaxies, stars, and planets to the formation and fueling of giant black holes in the centers of galaxies. Interstellar dust is extremely effective at absorbing visible, ultraviolet, and low-energy X-ray photons, re-emitting their energy in the infrared. Warm, dense interstellar gas cools predominantly through low energy fine structure lines and also emits profusely in rotational transitions of the most abundant molecules; both systems of lines emerge predominantly in the far infrared and submillimeter region of the spectrum.

This spectral region, therefore, holds the key to many fundamental questions. But because only a tiny fraction of the region can be observed from the ground, and because the necessary detector and cryogenic technologies simply did not exist until recently, this rich spectral region is almost completely unexplored. The combination of angular resolution, sensitivity, and wavelength coverage represented by SIRTF (2001) and FIRST (2007) will be orders of magnitude greater than previous capabilities, yet still orders of magnitude less than what will be required to answer some of the central questions already posed.

Recent and projected advances in detectors, interferometry, lightweight optics, and cryogenics will enable a far infrared mission by the end of the next decade with ~1" angular resolution at 100 μm, spectral resolution up to a few times 10^4, and the sensitivity to achieve high signal-to-noise ratios on moderate starburst galaxies at redshifts of 5 or higher.

Two mission options are being studied. The Space InfraRed Interferometric Telescope (SPIRIT) is an intermediate class mission

with five flat stretched-membrane mirrors along a 30-m deployable boom, selected two at a time by tilting flats that feed a two-beam telescope with a spherical primary mirror. A beam combiner includes a Fourier Transform Spectrometer (FTS) followed by dispersing elements and background-limited detector arrays, giving high sensitivity and spectral resolutions from 10 to 3×10^4 over the wavelength range 40–400 μm. All optics are cooled to roughly 4 K with a combination of passive and active coolers. The entire 30-m beam is rotated slowly to achieve excellent imaging capability. Launch would be on a Delta 2-class rocket. SPIRIT would have collecting area and angular resolution (in beam area) 30 and 1600 times, respectively, better than SIRTF, and 2 and 100 times better than FIRST. The instrumental background would be 10^4 times lower than FIRST because of the cold optics. The angular resolution of SPIRIT would allow the far infrared background to be resolved almost completely into individual sources.

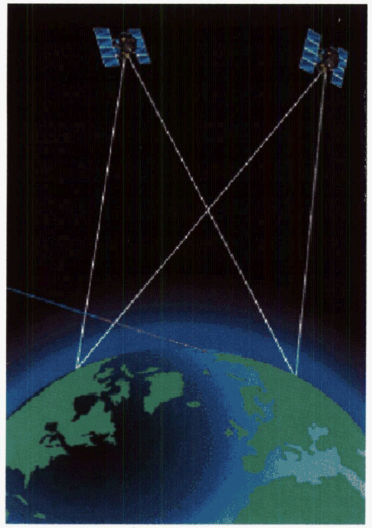
The second option being studied is a 10-m filled aperture telescope using lightweight, deployable optics cooled to ~4 K. SPIRIT and the 10 m would use similar detector arrays. The 10 m telescope would have collecting area and angular resolution (in beam area) over 100 times greater than SIRTF and 10 times greater than FIRST.

SPIRIT and the 10 m require similar technology developments in detector arrays, coolers, and lightweight, cryogenic optics. SPIRIT requires interferometric technology based on SIM and a deployable boom; the 10m requires lightweight, deployable mirrors based on NGST. The scientific interests of these projects overlap with the ASOPS Filled Aperture Infrared (FAIR) mission.

5.2.2 High Priority Missions

OWL. We know from ground-based observations that there are a few cosmic-ray particles with surprisingly high energy, greater than 10^2 eV. This flux is surprising because the cosmic background radiation makes the Universe opaque to protons and heavier nuclei originating from cosmological distances. Evidently, there must be some extremely powerful sources nearby, cosmologically speaking. We do not understand the identity of these particles—are they protons, iron nuclei, or even photons? Neither do we know their sources or how they are accelerated to such high energy. It has even been suggested that these highest energy particles may come from the annihilation of topological defects formed in the early Universe. If so, there also would be an accompanying, intense flux of similarly high energy neutrinos.

Detection of these particles requires special techniques. So far studies have been limited to ground-based telescopes that detect the shower of secondary particles they produce in the air, or atmospheric scintillation produced by those showers. Existing telescopes are so small that only a few of the very highest energy particles are ever likely to be seen this way. The Pierre Auger Observatory is a new ground-based detector under construction which is a much larger array of water-Cherenkov and atmospheric scintillation detectors. Auger's two sites (one in the northern and one in the southern hemisphere) will have full sky coverage but still will be limited to a relatively modest detector area. To achieve a larger event rate, it is necessary to go to space where a much larger area of the atmosphere can be monitored. In the OWL project, it is intended to use



OWL will detect the highest energy cosmic rays. The origin of these particles remains a mystery.

two high altitude spacecraft to obtain a stereo view of the light flashes from these rare cosmic-ray interactions to determine their arrival directions with accuracies of about one degree.

Energetic X-ray Imaging Survey Telescope (EXIST). There is a compelling need for a hard X-ray all-sky survey in the 10 to 500 keV energy range. The only previous survey in a subset of this energy range was performed by the A4 instrument (20–120 keV) in 1979. At both lower and higher energies, there have been recent surveys, and a new hard X-ray survey with limiting sensitivities around 0.1 mCrab will provide both a greatly improved understanding of the hard X-ray sky and a context for the surveys in adjacent energy ranges. The transition from thermal to non-thermal processes in many sources is expected in this range. Hard X-ray emission is especially important in the study of accreting neutron stars, galactic black hole candidates, sites of nucleosynthesis, active galaxies (including exploration of obscured AGN), and diffuse emission (including the extragalactic background).

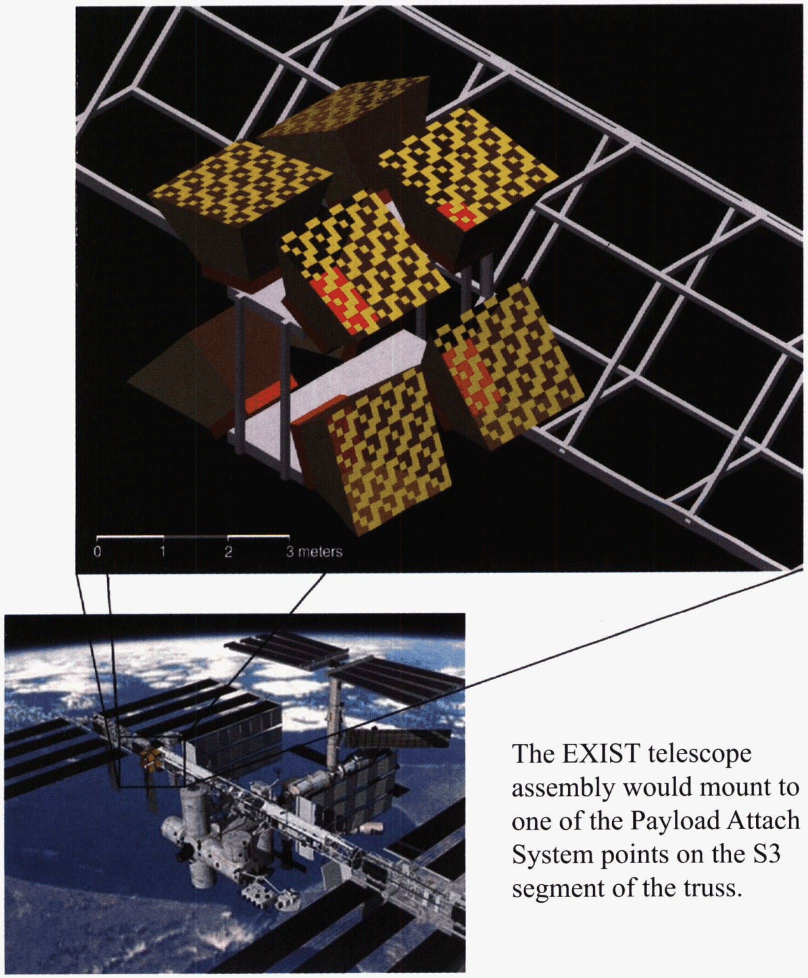
An excellent approach to this science is provided by the Energetic X-ray Imaging Survey Telescope (EXIST). EXIST is an Intermediate class mission which will give a factor of 100 improvement in sensitivity as compared to HEAO 1. The instrument is a wide-field coded aperture telescope. The technology for the detector plane is well in hand with new-technology solid state detectors becoming available that operate at room temperature. Technology development is needed to extend the operating range of these detectors from the current ~200 keV upper limit to 500 keV. With its wide field-of-view and survey nature, EXIST is a good candidate for placement on the International Space Station (ISS).

ARISE. A requirement for several SEU campaigns is to improve the angular resolution so that we can observe cosmic objects on smaller scales and understand better how they work. This is particularly true for quasars and other forms of active galactic nuclei. The black holes in the nuclei of nearby galaxies (including our own) subtend angles of order 1–10 μarcsec. Radio astronomers have developed a technique called Very Long Baseline Interferometry (VLBI) in which the wave amplitudes and phases at several separate telescopes are combined to obtain maps of the source structure. The angular resolution achieved is given by the quotient of the observing wavelength and the separation of the telescopes, and is limited by the size of the Earth to roughly 300 μarcsec from the ground.

To achieve still higher resolution requires the use of orbiting telescopes. The Japanese/US mission HALCA, launched in 1997, has taken the first step in this direction with a small orbiting telescope, and has demonstrated angular resolution a factor of three higher than can be achieved at the same frequency by ground-based arrays. The next step will require launching a larger and hence more sensitive telescope into a larger orbit. With a 25 m deployable telescope and extremely sensitive cryogenic receivers based on high-electron-

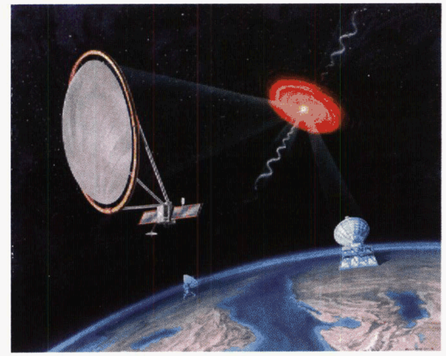
Energetic X-ray Imaging Survey Telescope (EXIST) on ISS

Conceptual layout of EXIST on ISS Integrated Truss Assembly



The EXIST telescope assembly would mount to one of the Payload Attach System points on the S3 segment of the truss.

EXIST concept on the International Space Station



ARISE will use VLBI radio observations to probe the inner regions surrounding massive black holes.

mobility-transistor technology, ARISE will be able to image the regions around black holes with 15 µarcsec angular resolution, equivalent in many sources to 100 light days or less! Such observations will answer many questions about how black holes are fed, how relativistic jets are formed, and how the high energy photons detected by gamma-ray telescopes are produced near black holes.

ARISE will also have the angular resolution and sensitivity to observe collections of powerful H_2O masers found within a few light years of the central black hole in galaxies, out to a distance of over 100 Mpc. Observing how such masers move in the gravitational field of the central black hole allows a direct measurement of the mass of the black hole itself, determination of the structure and dynamics of the accretion disk around the black hole, and a direct geometrical measure of the distance of the black hole and its parent galaxy.

ARISE requires technology development in several areas, including lightweight deployable optics, low-noise HEMT amplifiers, active cryocoolers for 20K, and very broadband (8Gb/s) downlink communications .

5.3 Visions Mission

We have identified six "vision missions", where either the science goals are clear, but the technology is not yet defined, or where the outcome of planned missions will dictate our future course, but where we can envision possible future questions. These vision missions address the highest priority scientific objectives that are currently foreseeable, allowing us to identify where technology efforts should aim over the next decade.

The Advanced Compton Telescope (ACT). The Microarcsecond X-ray Interferometric Mission (MAXIM), the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), and a Large Aperture UV/ Optical Telescope are aimed at identifiable but currently technically unachievable scientific objectives. MAP and Planck will revolutionize our understanding of the geometry and composition of the Universe but may yet leave the picture incomplete. While we cannot be certain of the outcome, we can envision that a CMB polarization experiment and a Sunyaev-Zeldovich Mapper are possible future steps in our quest to ultimately understand the Universe.

Advanced Compton Telescope (ACT). Observations in the energy range from 500 keV to 30 MeV explore a variety of astrophysical questions of fundamental importance. The continuum emission and nuclear line astrophysics involved provide unique information on galactic chemical evolution and supernova physics as well as important measurements for active galaxies, pulsars, and diffuse emission processes. Previous instruments operating in this energy range have provided detailed maps of galactic positron and ^{26}Al emission, as well as line emission detections from objects like SN 1987A (^{56}Co) and Cas A (^{44}Ti). To make breakthroughs in this area, however, will require large improvements in sensitivity and spatial resolution. The Advanced Compton Telescope (ACT) is the mission concept to supply these improvements. The ACT is a large Compton telescope, utilizing solid state detector technologies to provide the necessary energy and spatial resolution as well as background reduction. Technology development in large-volume solid state, high pressure gas or liquid detectors is needed to bring this concept to fruition.

X-ray Interferometry Mission. The "Grand Challenge" proposed is nothing less than the imaging of a black hole, allowing us to peer into a truly different part of space-time and making direct observations of the effects of General Relativity at the event horizon. This would give direct access to the relevant parameters of the central region without recourse to assumed models. It requires 0.1 μas angular resolution, which will also enable a new way of looking at many other science goals.

It has been pointed out that angular resolution at this level is equivalent in many ways to "going there." Nearby stellar coronae can be imaged with very nearly the same detail that we see on the Sun from a good telescope based on the Earth. Some of the other science that will become accessible includes:

- direct imaging of hot gas transfer in close binary systems, including imaging the disk of the white dwarf
- watching a supernova blast wave evolve in a distant galaxy
- detailed studies of the coronal morphology of thousands of stars
- direct imaging of the accretion disk structure in AGN, along with its relation to the base of the jets
- detailed studies of disk formation in protostars

The design of the MAXIM mission could be similar to that proposed for the Pathfinder. The mirrors would now have to be on separate spacecraft to obtain the 1 km baselines required, and there would probably be a number of baselines of different length and

angles, so that all W-plane coverage could be obtained simultaneously. (This will be required for many objects since these small systems can change very fast!)

Submillimeter Probe of the Evolution of Cosmic Structure. SPECS is a bold new concept for a mission that would look back to the epoch of fragmentation of matter in the early Universe and watch how galaxies form. Following mid-term missions that would first detect these newly formed galaxies, SPECS will measure the composition, density, temperature, and velocities within their proto-galactic clouds. Using these measurements, we will be able to map out for the first time the process of galaxy-building. With an ensemble of cold telescopes, each several meters across, covering baselines at L2 up to a kilometer, SPECS will provide spatial resolution in the far infrared and submillimeter part of the spectrum that is similar to that now achieved by HST in the optical or is foreseen for NGST in the near IR. But unlike these latter missions, SPECS will see new galaxies even before they completely form and give birth to stars.

The technological basis for SPECS will be established by near-term and mid-term missions. These would provide breakthroughs in detector technology and techniques for long-baseline interferometry in space, including in particular accurate formation flying and station keeping (perhaps using tethers). SPECS is thus both the scientific and technological culmination of a series of groundbreaking missions that are key parts of our Roadmap. The ASOPS theme is also very interested in these goals.

Large Aperture UV/Optical Telescope. Hubble Space Telescope, with its extraordinary combination of high image quality and sensitivity throughout the ultraviolet and optical wave bands, has led to great advances in our understanding of the structure and evolution of the Universe. But by 2010, it will have fallen far behind its ground-based counterparts, leaving a tremendous gap in our understanding between the local Universe and the distant, high redshift Universe that, in look-back time, covers most of the history of the Universe. Further advances will require a new ultraviolet/optical space telescope with sensitivity at least 10 times greater than that of the Hubble Space Telescope, even with its most modern and advanced detector systems. A key goal of such a mission will be detailed study of the distribution of neutral and ionized gas over the history of the Universe, from the formation of galaxies to the present epoch. The evolution of the largest known structures in the Universe, the gaseous sheets and filaments that pervade space and comprise most of the normal (baryonic) mass of the Universe in the distant past, can be observed only against bright background sources such as the most distant quasars. To map out these structures requires observing many closely spaced background sources; this requires high sensitivity because bright background sources are rare but fainter sources are much more common. An 8-m class telescope, with more than 10 times the primary mirror area as HST, will allow exploration of these structures on scales of about 10 arcminutes, which corresponds to megaparsec scales throughout most of the history of the Universe. The scientific issues discussed here overlap with the SUVO project discussed in the ASOPS roadmap. Over the next decade, several key technologies will need to be developed in order to place an 8-m telescope into space. These include development of large lightweight precision mirrors, advanced ultraviolet detector systems, and improved reflective coatings for ultraviolet optical elements such as mirrors and dispersive gratings.

Cosmic Microwave Background Polarization Experiment. If MAP and Planck confirm the inflationary predictions of a flat Universe and primordial perturbations, then the next obvious step will be to further test inflation and to determine the new physics responsible for inflation. Inflation predicts the existence of a cosmological background of gravitational waves that can be detected only via

the unique CMB polarization pattern they produce. If the energy scale of inflation was well below that expected in grand unified theories (GUTs) of particle interactions, then the polarization pattern will be too small to be detectable. However, if inflation was related to GUTs, as most theorists surmise, then the CMB signature is probably detectable with a dedicated post-Planck CMB polarization satellite. Detection of this polarization pattern would provide a "smoking-gun" signature of inflation and determine the new physics responsible for inflation. It would provide a unique probe of new physics at energy scales well beyond those accessible with accelerator experiments and provide a window to the early Universe, only 10^{-36} seconds after the big bang! The CMB polarization is also required to unambiguously reconstruct the spectrum of primordial perturbations. It can discriminate between competing models for structure formation, constrain the ionization history of the Universe, and thus probe the earliest epochs of star and AGN formation in the Universe. Current uncertainties in foregrounds and in relevant details of structure-formation models require that we wait for results at least from MAP and possibly from Planck to determine the precise specifications for a polarization satellite. However, it is likely that the satellite will require an angular resolution of order 0.1 degrees and a detector sensitivity possibly two orders of magnitude better than Planck. Observations in a wide range of frequencies will be required to subtract foregrounds and full-sky coverage will likely be needed. Although such a program presents serious technical challenges, it is likely achievable (at least in part) in the next decade with a focused technology development program.

Sunyaev-Zeldovich Mapper. The hot electron gas in clusters can scatter cosmic microwave background (CMB) photons and thus distort the energy spectrum of CMB photons observed coming through clusters. This Sunyaev-Zeldovich (SZ) effect will provide a unique probe of the high-redshift Universe. It can be used in principle to measure the Hubble constant and deceleration parameter, determine the peculiar velocities of clusters, and the abundances of clusters. Until recently, it was believed that these goals could only be achieved with X-ray observations that determine the cluster's electron temperature, and if so, this would limit the primary utility of the SZ effect to lower redshifts. However, recent work has shown that sufficiently precise multi-frequency measurements of relativistic SZ distortions can determine the electron temperature. In recent years, the SZ distortion has been successfully mapped in several clusters at centimeter and 2-mm wavelengths. The technology for a space-based SZ Mapper capable of carrying out these science goals should be available in the post-Planck era. The experiment would require arcminute angular resolution and instrumental sensitivity that improves slightly on that of Planck. Maps covering the range 30–400 GHz will be needed, and lower (5–10 GHz) and higher (1000–3000 GHz) frequencies will be needed to aid in subtraction of unrelated foregrounds. Both filled-aperture and interferometric telescopes are being considered, and an aperture (or baseline) of roughly 10 meters will likely be required.

5.4 Scientific Missions Beyond the Horizon

The SEU quests will not be fulfilled with the suite of missions proposed for the Strategic Plan for the midterm, nor even with the more challenging vision missions. We can already identify science questions requiring technologies beyond the current development plans. In this section, we identify some compelling scientific questions from our Quests and Campaigns that will likely develop into mission concepts as a result of the returns from the missions identified above.

Relic Gravitational Wave Background. To test our theories of the very early Universe, such as the inflation theory, and nail down the details of the big bang through observations, we might need to image the Universe beyond the barrier at recombination (300,000 years), and potentially observe the Universe less than 1 second after the big bang. Electromagnetic radiation cannot penetrate the recombination barrier, but gravitational waves from the big bang fill the Universe now. A mission containing two independent gravitational wave interferometers, each 1000 times more sensitive than LISA, can detect the gravitational background predicted by standard inflation theories and provide the first observational probe of structure in the very early Universe.

Probing the First Structures in the Universe. The first structures in the Universe probably form at $z > 10$. X-ray emission, unlike other wavelengths, will penetrate the dense environments expected in the early Universe. The best way to find the first collapsed structures in the Universe, either the first black holes or the signatures of early galaxy formation, may be with X-ray observations. The very large collecting areas and sub-arcsecond angular resolution required might involve multiple spacecraft containing vary large area focusing optics and, many kilometers distant, spacecraft containing focal plane instruments.

Gamma-ray Bursts. Gamma-ray bursts are one of the most exciting and scientifically important phenomena in astrophysics. Future missions beyond HETE-II and a gamma-ray burst Explorer will be required to fully understand and exploit them. However, the decision on what wavelength band and instrumental capabilities are optimum for future progress must await results from upcoming missions.

The Physics of Supermassive Black Holes. GLAST will provide important data on the physics of supermassive black holes and the accretion processes taking place at the cores of active galactic nuclei. Resolving the sites of high energy gamma ray production within the host galaxy and its jet may be required to confirm details of these processes as well as examine potential sites for the creation of exotic particles and high energy cosmic rays. This will require a focusing telescope for high energy gamma rays, a requirement which is beyond the horizon of the missions and mission concepts discussed in this Roadmap.

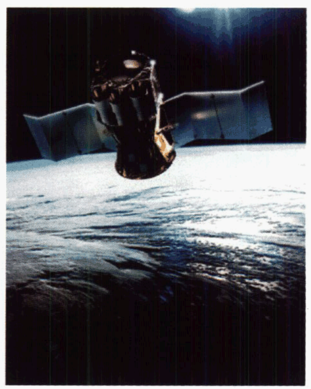
6 Explorer Program

NASA's Explorer program is a vital element of the SEU science enterprise. It offers frequent opportunities to carry out small and intermediate-sized missions which can be completed and launched on a short (approximately four-year) timeframe. Small and Medium Explorer (SMEX and MIDEX) missions, which are scientifically more focused than large-scale missions, can address some of the most significant scientific topics in the Structure and Evolution of the Universe theme. For example, MAP (described previously), which will be the pioneer mission in the MIDEX program, will answer fundamental questions about the age and mean matter density of the Universe, beginning a new era in cosmology and astrophysics in a significantly shorter timeframe and for a fraction of the cost of a large Explorer or Great Observatory mission.

Two Small Explorers (SMEX) missions, SWAS and GALEX, provide key elements of the SEU program:

The Submillimeter Wave Astronomy Satellite (SWAS). SWAS is a NASA Small Explorer Project (SMEX) launched in December 1998. Its principle objective is to better understand the process of star formation through observations of water, molecular oxygen, isotopic carbon monoxide, and atomic carbon.

Results from early SWAS observations of both giant and dark cloud cores, evolved stars, external galaxies, and planetary nebulae confirm some elements of our prior understanding of interstellar chemistry. They also pose several new puzzles. In particular, SWAS has confirmed that warm ($T > 300$ K) molecular gas gives rise to abundant water—on a par with the abundance of CO or greater. However, the water detections toward many cooler gas regions suggest much lower water abundances than predicted by at least a factor of 100. These findings, coupled with the non-detection of molecular oxygen, indicate that our understanding of the oxygen chemistry in the ISM may need to be revised. Since oxygen is the most abundant element after hydrogen and helium, new questions about the validity of the oxygen chemistry in the ISM have a significant effect on our understanding of the chemistry of other elements that interact with oxygen bearing species, such as carbon, nitrogen, and silicon. In addition, SWAS has conducted spectroscopic studies of Mars and Jupiter and recently provided the first direct detection of water evaporation from a newly discovered comet—Comet Lee.



The SWAS SMEX mission is improving our understanding of star formation by observing water, molecular oxygen, isotopic carbon monoxide, and atomic carbon.

The Galaxy Evolution Explorer (GALEX) is a SMEX mission that will map the global history and probe the causes of star formation over the redshift range $0 < z < 2$, 80% of the life of the Universe, the period over which galaxies have evolved dramatically, and the time that most stars, elements, and galaxy disks had their origins. GALEX uses the space ultraviolet to simultaneously measure redshift and star formation rate (using the UV luminosity).

GALEX will perform spectroscopic and imaging surveys of the sky during its 28-month mission, measuring 100,000 galaxy spectra in one year. GALEX will launch in 2002.

Prospective Future Missions. Contributions by future Explorer missions to our understanding of the structure and evolution of the Universe promise to be equally important. Each solicitation for proposals elicits many more high-quality experiments than can be implemented. Peer review, the ability to implement new, creative ideas and react quickly to recent scientific discoveries, is essential elements of the "faster, better, cheaper" philosophy which lies at the heart of the Explorer program. Suggesting a queue of future explorer missions would countermand this mandate.

To illustrate the science which is possible with Explorer class missions, we list in Table 1 mission concepts which are mature and which have been proposed or studied as SMEX and MIDEX experiments. This list is necessarily incomplete and will change over time as technology matures and new and creative ideas emerge.

MISSION	PRIMARY SCIENCE	INSTRUMENT GOALS	SIZE	TECHNOLOGY
Dark Matter Campaign				
Microwave Background Spectral Mapper	Low-frequency distortions of Cosmic Microwave Background CMB spectrum	15 degree Field of View (FOV) All-sky coverage	MIDEX	HEMT amplifiers
Deep X-ray All-sky Survey	Map large sample of galaxy clusters to survey large scale structure	> 20 times fainter than ROSAT	MIDEX	High-throughput grazing incidence optics
Cosmological Helium Probes	Measure $^3He/^4He$ isotope ratios in local Universe He Gunn-Patterson effect	Extreme Ultraviolet/Far Ultraviolet (EUV/FUV) spectroscopy	MIDEX	Grating spectrometer
Elements Campaign				
Cosmic-Ray Trans-Iron composition explorer	Test models of galactic cosmic rays; search for freshly-synthesized supernova material	Composition for $14 < Z < 92$	MIDEX	Cherenkov and silicon detectors
Positron explorer	Study positron cosmic rays, especially those produced by decay of radioactive aluminum	20 MeV–2 GeV	MIDEX	Permanent magnet particle tracking
Heavy cosmic-ray composition explorer	Determine age and time of acceleration for heavy cosmic rays	High-statistics measurements of U, Th	SMEX	Glass track etch detectors
Far IR imager	Study cold interstellar dust	Coverage: 100–300 µm Wide FOV	MIDEX	Bolometer array
X-ray spectral line mapper	Study conditions, abundances, and dynamics in supernova remnants and galaxy clusters	$\Delta E \sim 5$ keV; 0.1–2 keV	MIDEX	Bragg crystals with grazing multicoated optics
Very low-frequency radio array	Study supernova remnant shock emission	Coverage: interplanetary plasm frequency to ionospheric cutoff (10 kHz–30 MHz)	MIDEX	Formation flying antenna array
UV spectroscopic survey	Survey starburst galaxies Study star formation and evolution from Z = 0–2	90–120 Å 120–280 Å spectroscopy	MIDEX SMEX	Channel plate detectors Lightweight optics
Cycles Campaign				
Diffuse soft X-ray background explorer	Study the distribution, dynamics, and thermal history of the hot component of the interstellar medium (ISM)	Sensitivity, resolution to detect key live emission complexes	SMEX	Wide-field telescope bolometers or tunnel junctions
Far-infrared spectroscopy mission	Understand origin of stars and recycling of interstellar gas	$\lambda/\Delta\lambda > 10^6$ sensitive in 1–3 THz	MIDEX	Hot electron bolometer mixers

MISSION	PRIMARY SCIENCE	INSTRUMENT GOALS	SIZE	TECHNOLOGY
Cycles Campaign (continued)				
UV diffuse spectral imager	Study hot ISM in our and other galaxies	Spectroscopy 90–120 nm 120–280 nm	SMEX	Diffuse grating spectrometer
Disks and Jets Campaign				
Hard X-ray All-sky Survey	Observe hidden AGN Determine origin of the hard X-ray background	All-sky coverage 10 arcmin resolution 10–511 keV	MIDEX	Coded aperture Solid state detector
High-resolution X-ray Imager	Image jets in AGN Study nuclei of nearby galaxies	0.1" angular resolution	MIDEX	Polished spherical optics
UV Imaging Survey	Understand geometry and structure of active galactic nuclei	All sky UV coverage 90–280 Å	SMEX	Channel plate detectors Normal incidence optics
High Energy Campaign				
Arcsecond localization explorer	Provide arcsecond error boxes for deep counterpart search	1" error box for several dozen bursts	SMEX MIDEX	Coded aperture/grid or timing satellites
Rapid positioning telescope	Detection of transient counterpart at other wavelengths	Sub-degree positions within minutes	SMEX	Coded aperture telescope
High-sensitivity Imager	Search for cosmological signatures, spatial anisotropy toward nearby galaxies	Factor 20 fainter than BATSE; sub-degree positions	MIDEX	Coded aperture telescope
Gravity Campaign				
Polarimetric Explorer	Understanding where and how X-rays originate from around black holes and neutron stars	X-ray polarimetry of the brightest cosmic X-ray sources	SMEX	Thompson scatterer position sensitive X-ray detector
Redshift experiment	Test local position invariance by measuring gravitational redshift	Improve current accuracy by two orders of magnitude	SMEX	Flight-qualified precision frequency standard
Equivalence principle experiment	Test universality of free fall independent of chemical composition	Improve current accuracy by three orders of magnitude	SMEX	Laser interferometer
Test of relativistic gravity	Measure space curvature per unit mass	Improved accuracy by $\geq$ two orders of magnitude	SMEX MIDEX	Optical transponder drag-free system

7 Suborbital Program

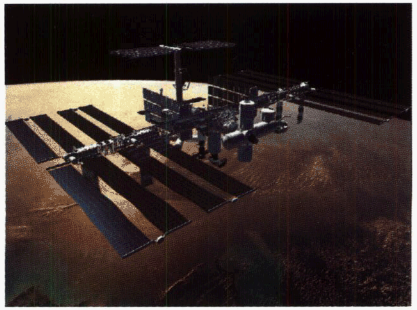
NASA's balloon and rocket programs are essential to the SEU program. The balloon program in particular has been responsible for significant scientific discoveries. Equally important, however, is the role that both balloon and rocket experiments play in developing and demonstrating new instrumentation and technologies for space application. In addition, these programs are based in large part in universities and are responsible for training new generations of instrumentalists.

Many pioneering discoveries in astrophysics were made from balloons and rockets. For example, gamma-ray lines from radioactive elements synthesized in supernova remnants, gamma rays from the annihilation of electrons and positrons in our Galaxy, and the sources of high-energy radiation from the center of our Galaxy were all discovered by balloon-borne instruments. Currently, balloon instruments are providing unique measurements of the arcminute-scale anistropies in the cosmic microwave background, high-energy emission from Galactic black holes, the isotopic composition of cosmic rays, and the width of the ^{26}Al gamma-ray line emission from the Galaxy with capabilities not available on any existing satellite. The observational capabilities of balloon instruments would certainly take a great leap with the development of a long-duration capability, with flights extending over periods of weeks.

The role that rocket and balloon experiments play in demonstrating instrument concepts and key technologies for space cannot be overemphasized. All of the Chandra focal plane instruments were first demonstrated on rocket flights. It is important to recognize that this is increasingly true in the new "faster, better, cheaper" era, with an aggressive Explorer program which aims to develop and construct satellite instruments in very short time frames. To reduce the risk, ensure success of new, enabling technologies, and guarantee mission schedule, instrumentation must be prototyped and demonstrated prior to Phase A. Balloons and rocket experiments are ideal platforms for this demonstration.

NASA has committed to the development of a new lighter-than-air carrier capable of supporting flights of > 100 days in the stratosphere with a one-ton scientific payload. This carrier will be tested on a flight to circumnavigate the globe in December 2000. When the capability of this new carrier is fully realized, it will be competitive with other NASA carriers. The current 10-day balloon flight capability will be included in the next SMEX AO and the new carrier will be available in all future Explorer AOs. This new opportunity promises large carrier cost reductions and unique capabilities (multiple reflights, polar day/night flights, low charged particle background) which will significantly enhance missions in many areas of space and Earth science including astronomy in the submillimeter to far-infrared (Cosmic Microwave Background studies), hard X-rays to gamma rays (black holes, AGN, and nucleosynthesis), and cosmic rays. These Explorer payloads will be significantly more ambitious and expensive than traditional suborbital payloads, but they will still capture many of the traditional advantages of suborbital missions.

Finally, these programs play a crucial role in educating new generations of scientists and engineers. Since the timescale of these experiments coincides with the typical graduate student tenure, students have the opportunity to participate in all aspects of an instrument, including design, fabrication, scheduling, and launch. It is not, therefore, surprising that many of the premier experimental astrophysicists in the country had their start working on rocket and balloon instruments.



The International Space Station will offer unique capabilities for selected SEU missions.

8 The International Space Station

The International Space Station (ISS) will offer unique capabilities from which research can be conducted. Instrument accommodation on externally attached exposed sites provide exposure and viewing over most of the sky. The combination of the Shuttle launch capability and the ISS power and data infrastructure make this carrier particularly appropriate for astrophysics missions with large mass, volume, and data rate but minimal pointing requirements. Several high science return missions have been identified as particularly appropriate for ISS including ACCESS, a high energy cosmic-ray experiment, and EXIST, a hard X-ray all sky survey.

As the ISS construction phase becomes more mature over the next few years, initiatives are being developed to study the use of external attachment points for astrophysics research. Since the ISS maintains an international character, instruments built and operated by scientists from many nations are expected to play a major role in this activity. The ISS also has the unique capability to provide routine astronaut servicing of instruments on orbit and this could facilitate investigations of wider scientific scope and longer lifetime in comparison with other carriers.

9 Outreach and the Public Mandate

Space science has captivated the public interest. From the possibility of life on Mars, to bursts of gamma rays that are momentarily brighter than the entire Universe, to magnetars that could pull the keys out of your pocket at the distance of the Moon, the excitement of exploration and discovery is manifest in what we do. Our discipline takes people to the frontiers of the cosmos and opens their eyes to the richness of the natural world on the largest scales.

Space science addresses questions that are exciting and readily communicable to a broad audience. It has produced a stream of fundamental and unexpected discoveries that have been eagerly publicized by the media and hungrily consumed by the public. Within the last decade in particular, space science has developed capabilities and techniques to address, through the critical eye of the scientific method, very basic questions about our place in the cosmos.

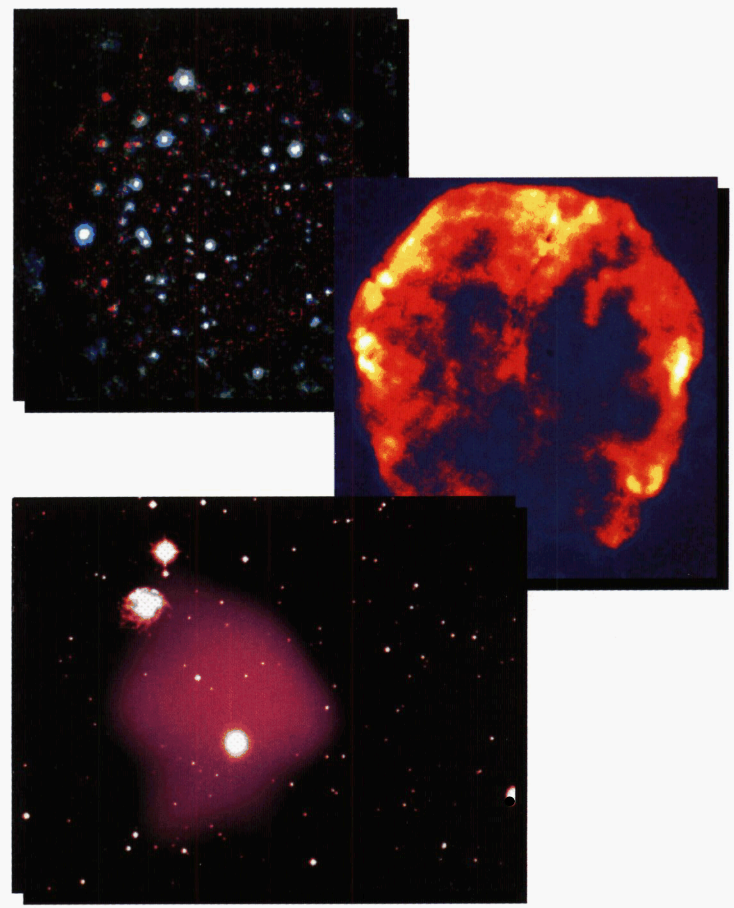
Major space science missions that address these fundamental issues are expensive. The necessary funding can only be accomplished as a national priority, fueled by the curiosity and inquisitiveness of a nation of true pioneers. The taxpayers, and the American public in general, are our partners in these endeavors, and we are committed to bringing them along on our journeys of discovery.

The SEU Theme recognizes the importance of a strong public mandate for the enterprise. Our outreach efforts are dedicated to communicating the discoveries and opportunities of our discipline to these partners-in-exploration. All SEU missions are designed with public outreach as a core element. Inviting and illuminating Web sites have become the de facto standard for making the real-time connection between our missions and the public. These sites allow

The Public Appeal of SEU: *What's Out There?*

We need a good map and a weather report…

- **How did the Universe begin and proceed to form complex structures?**
- **How is matter recycled and reformed through the Universe?**
- **What is the mysterious material that comprises over 90% of the mass of the Universe?**



The Public Appeal of SEU: *Pushing the Limits*

To reach for the stars, we must understand the limits of our Universe

- **Gravity:** ***black holes, gravitational waves***
- **Space:** ***antimatter, dark matter, exotic matter***
- **Time:** ***maps of the earliest light, the most distant objects***

The SEU Missions are the *Cosmic Journeys*, fundamental to our Reaching for the Stars

the public not only to learn about the goals of a mission but to follow along with us as we plan, build, and launch them and finally harvest their discoveries. See for example the Imagine the Universe site at http://imagine.gsfc.nasa.gov. Note also the Chandra site at http://chandra.harvard.edu which exemplifies the way that materials for the public and scientific resources for astronomers are packaged together. Our outreach efforts are aimed both at the general public and at young students. While these latter efforts, at all levels from kindergarten through colleges and universities, contribute to the scientific literacy of our nation, it is the excitement about science and the passion for discovery we bring to them that will most fundamentally serve the needs of our country in the next generation.

The Office of Space Science has ambitious plans to strengthen its educational role though curriculum development, teacher training, and facilitating connections and partnerships between the space science and educational communities. The SEU theme supports this work by providing materials that can be integrated into educational curricula conforming to national standards. The Universe! Forum (see http://cfa-www.harvard.edu/seuforum/) serves this purpose for SEU as a public gateway to research results educational materials and scientific expertise.

Outreach is an integral part of our SEU mission and the connection that it fosters between the public and the science community is enlightening to all.

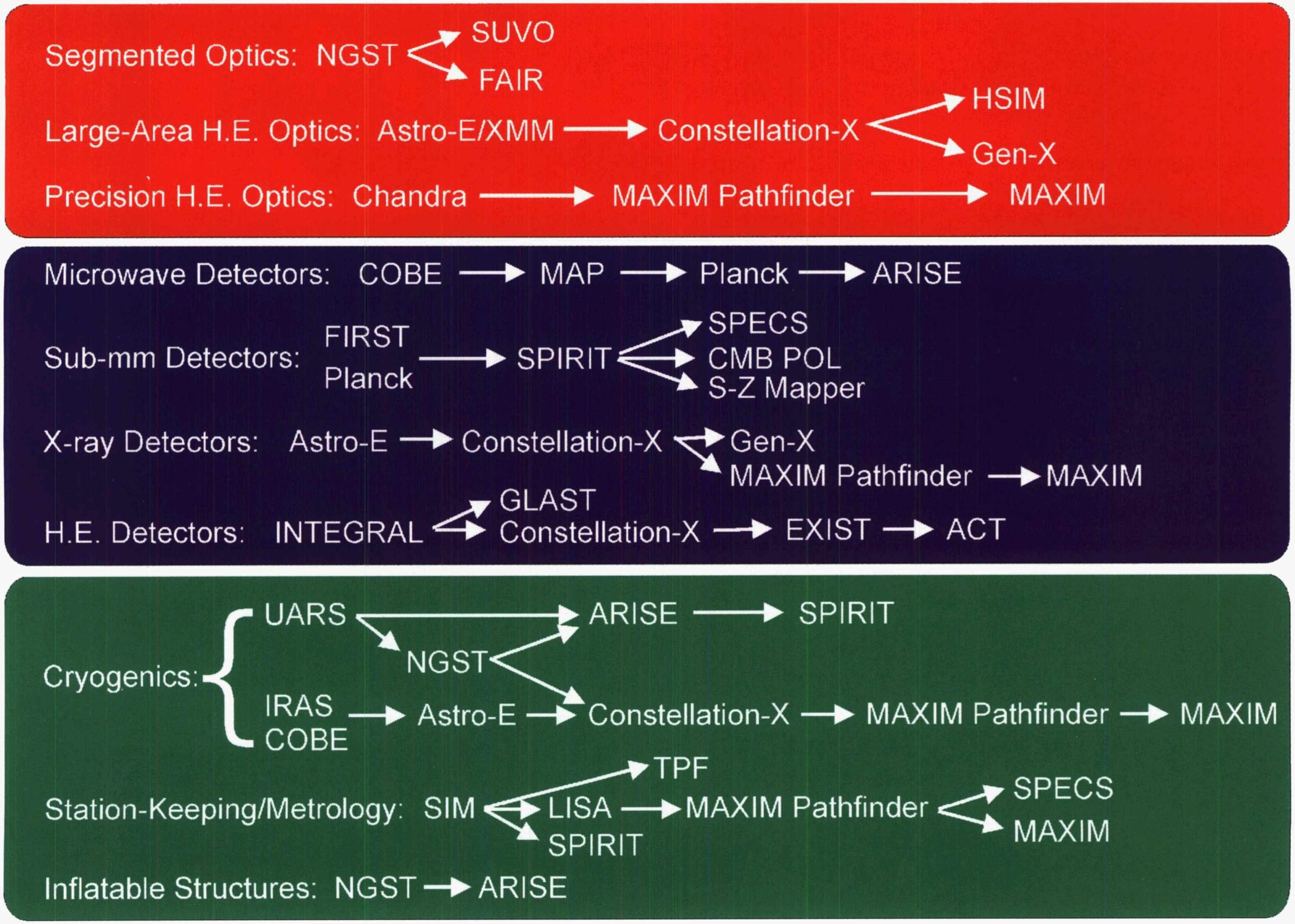
10 Technology

The technical content of the SEU Roadmap is extremely diverse a consequence of the wide-ranging nature of the SEU investigations themselves. Of paramount significance is the enormous range in the nature and energy of the radiation and particles to be detected. The SEU missions tackle fundamental questions through gravity waves and cosmic-rays and across more than twenty decades of the electromagnetic spectrum.

The SEU Technology Roadmap has been developed by the Structure and Evolution of the Universe Technology Working Group (SEUTWG) through broad-based community input from scientists and engineers in academia, government, and industry. This Roadmap is guided by five key principles:

1. *Close Coupling of Technology Development to Scientists.* Scientists are the end-users of these technologies and must be kept intimately involved in the development programs to ensure that their needs are met.
2. *Balance.* While emphasizing near-term mission goals, the program is balanced to enable revolutionary technology developments that may lead to dramatic scientific breakthroughs in support of our "mid-term" and "vision" mission.
3. *Return on Investment.* Highest priority is reserved for programs that demonstrate that technological investment will lead to significant progress. SEU will follow an integrated strategy that coordinates technology developments for different programs and leverages technology advancements from academia, industry, and government to insure maximum return on investment.
4. *Peer Review.* Community oversight is essential to maintain a well-focused and efficient program that is responsive to scientific needs.
5. *Integrated Technology Strategy.* SEU will coordinate its technology developments with the other Space Science themes to identify leveraging and cost sharing opportunities.

Examples of Technology Development Pathways



This technology Roadmap is organized as follows: First we present the focused technology development programs for the top-priority near-term science missions in the 2003-2007 time frame, Constellation-X and the Laser Interferometer Space Antenna. Next are the mission-specific Roadmaps for each of our "mid-term" (2008–2013) and "vision" (2014 and beyond) missions. Finally, we describe the general cross-cutting technology areas that enable these exciting missions: high performance optics, next-generation detectors, advanced cryocooler systems, and formation flying.

10.1 Top Priority Near-Term Science Missions

10.1.1 Constellation-X

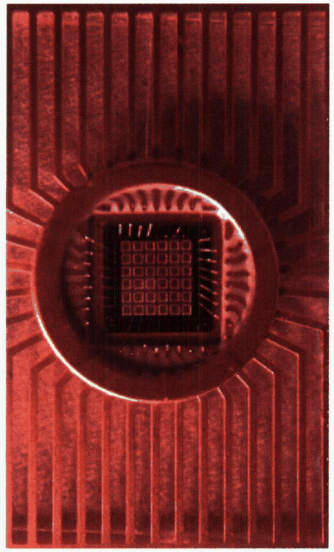
Constellation-X will use two sets of telescope systems on each of the four satellites: 1) a high throughput spectroscopy X-ray telescope (SXT) for the low energy band up to 10 keV, and 2) three hard X-ray telescopes (HXTs) for the high energy band. The SXT will use highly-nested light-weight grazing incidence X-ray optics coupled to an array of micro-calorimeters plus a reflection grating/CCD system. The calorimeter array will be cryogenically cooled to 50 millikelvins. The HXT will employ multilayer-coated grazing incidence optics coupled to a solid state CdZnTe or similar imaging spectrometer. An extendible optical bench will provide a 10-meter focal length for both telescope systems on-orbit yet allow two satellites to fit within a single fairing for launch.

Constellation-X Technology Development Requirements:

- Lightweight (areal density ≤ 1 kg/m^2), 5–15 arcsec X-ray optics
- X-ray Calorimeters
- Reflection Gratings and CCD detectors
- 3–5 K and 50 mK Coolers
- Hard X-ray focusing optics and CdZnTe detectors
- Extendible Optical Bench

Spectroscopy X-ray Telescope Optics. Constellation-X will use a Wolter Type I design of nested, grazing-incidence X-ray mirrors to focus X rays. The mission effective area (15,000 cm^2 at 1 keV) can be achieved with four mirror assemblies, each having a diameter of 1.6 m. Because X-ray optics must work at grazing incidence angles of typically 1 degree, the total reflective surface required is of order 50 times larger than the effective collecting area. The raw reflecting surface is equivalent to ~8 meter diameter optical telescope. The areal densities required for these heavily nested shells are of order 1 kg/m^2 with an optical figure requirement of 15 arcseconds Half Power Diameter (HPD) and a goal of 5 arcseconds. Replication techniques will be used in which each shell, or segment of a shell, is duplicated from a precisely shaped mandrel. The state of the art for the replicated shell technology, defined by the optics developed by ESA for XMM, meets the Constellation-X 15 arcsecond resolution yet requires mass reduction by a factor of six to meet the Constellation-X weight budget of 750 kg per mirror assembly. The alternate method of replicating X-ray optics in segments has been demonstrated to be within the Constellation-X weight budget, but spatial resolution needs improvement by at least a factor of six over the 1.5 arc minutes HPD achieved for the ASTRO-E optics.

X-ray Micro-calorimeters. Constellation-X will use an X-ray microcalorimeter at the focus of the SXT optics to detect photons from 1.0 to 10 keV with an energy resolution of 2 eV. The field of view and spatial resolution requirements necessitate a 30 by 30 pixel array with 250 micron pixels. Significant advances are required over the state of the art on ASTRO-E, which has 10 to 12 eV resolu-



Microcalorimeters at the focus of the Constellation-X spectroscopy telescopes will provide high-resolution spectroscopy with unprecedented sensitivity. Current devices must be scaled from single to large numbers of pixels.

tion in a 32 pixel array. Both transition edge sensor (TES) and neutron-transmutation-doped (NTD) technologies are being pursued. Recent laboratory development has yielded single pixel TES devices with resolution of 2.0 eV at 1.5 keV and 4.5 eV at 6 keV. It would be very beneficial to the mission science that the size of the calorimeter array be increased as much as possible. Development of multiplexing SQUID readouts is fundamental to achieving this goal.

The X-ray calorimeters require cooling to ~50 mK to minimize the magnitude of thermal fluctuation noise. The state of the art for such cooling, as used for the XRS system on ASTRO-E, consists of solid neon surrounding liquid helium providing a heat sink for an adiabatic demagnetization refrigerator (ADR). This technology is too heavy and has too limited a lifetime for Constellation-X. A mechanical cooler, such as the turbo-Brayton, is a better candidate for meeting the Constellation-X weight, power, size, and cost constraints.

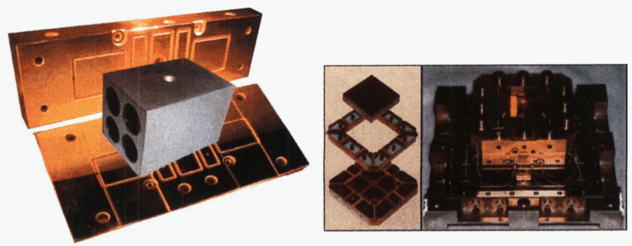
Gratings/CCD Arrays. Reflection gratings coupled with CCD detectors are the most promising technology to achieve the required spectral resolution and quantum efficiency over the 0.25 to 1.0 keV band. The baseline reflection grating spectrometer design utilizes an array of thin reflection gratings mounted at grazing incidence immediately behind the SXT optics. A fraction of the incoming photons are picked off by the gratings and dispersed onto a strip of CCD detectors. To improve the mass, cost, and reproducibility of the gratings over the *XMM* heritage, fabrication techniques using interference lithography are being investigated. Resistive gate CCD designs offer a number of advantages over conventional X-ray CCD architectures, including lower power, less susceptibility to radiation damage, and high production yields.

Hard X-ray Telescope (HXT) System. The HXT will cover the energy band from 6–40 keV (possibly up to 100 keV) with an effective collecting area of 1500 cm^2 at 40 keV. The HXT mirrors require tightly nested, light-weight substrates (similar to but smaller radius than the SXT) coated with multilayer structures which greatly enhance the reflectivity at high energies. Either replicated shell or segmented optics technology can be used to achieve the required $1'$ spatial resolution. High atomic number solid state CdZnTe or pixel detectors will provide the required spatial spectral resolution.

10.1.2 LISA

LISA detects the passage of gravitational waves by measuring relative changes in the path lengths of a three-arm interferometer. The arms are defined by inertial test masses enclosed in three separate spacecraft 5×10^6 km apart at the vertices of an equilateral triangle.

Each spacecraft will contain two optical assemblies, each having a transmit/receive telescope and a test mass and interferometer op-



The LISA mission requires development of inertial sensors of the kind shown here.

tics in a glass housing. Laser beams will be exchanged between spacecraft using a transponder scheme. The three arms between spacecraft will constitute three interferometers which can monitor both polarizations of gravitational waves or provide redundancy in the event of failure. The position of a spacecraft relative to its two test masses will be monitored electrostatically and controlled to their average position using micro-newton electric-ion thrusters. This "drag-free" operation will reduce the residual non-gravitational forces to an acceptable level. The three spacecraft, each attached to a propulsion module, will be launched aboard a single Delta II launch vehicle into an Earth-escape orbit. The propulsion modules will maneuver the spacecraft into their operational orbits and then be jettisoned. The orbits are selected to preserve the triangular formation without maneuvers and to take advantage of the benign interplanetary environment.

LISA Technology Development Requirements:

1. Inertial sensors
- Test mass with low magnetic interaction with solar field
- Position sensing for nanometer control of spacecraft position

2. Electrical discharge system to remove charges induced by cosmic rays
3. Micro-newton thrusters
- Drag-free control
- Thrust 2–20 μN to oppose solar pressure
- Controllable to 0.1 μN for nanometer positioning
- Long lifetime

4. Interferometry system
- Precision < 10 pm
- Stability over 10^{-5} to 10^{-1} Hz

5. Pointing < 10 nano-radian
6. High power laser
- 1 W continuous
- Frequency stability < 10 Hz
- Long lifetime

10.1.3 ACCESS

ACCESS is a large detector for high energy cosmic rays to be deployed as a Space Station attached payload. The principal detector elements of this instrument are: 1) Charged particle energy loss detectors for identification of the cosmic ray nuclear charge; 2) A transition radiation detector for measurement of high energy particle velocities; and 3) A calorimeter for the detection of particle energies.

The charged particle detectors require the development of large-area silicon pixel detectors with a large dynamic range of readout and millimeter spatial resolutions. Similar silicon detector structures have been used in ground-based charged particle detectors, but the large dynamic range in readout signal needed for the ACCESS detectors presents a new technical challenge. The development of a high dynamic range ASIC for the ACCESS pixel detectors is key.

The ACCESS transition radiation detector uses a large number of gas-filled detector tubes for the transition radiation X-rays generated in the radiator material. A key issue in this detector is the fabrication of a tube design using materials sufficiently thin to admit X-rays but which have low leak rates for the detector gas. Several materials have been identified as candidates for the tube material and prototype tubes and detector systems are being developed.

The calorimeter consists of solid material instrumented with charged particle detectors for the showers of secondary particles produced by incoming cosmic rays. The key issue is to supply sufficient segmentation to allow the reliable measurement of the shower size and identification of the incoming particle which produced the shower. The development of the pixel silicon detector discussed above is a crucial component of this calorimeter.

The detector technology for ACCESS is verified by direct testing at particle accelerators and through demonstrations in balloon flight instruments. These technologies need to be in place for the ACCESS design phase in 2002. The deployment of ACCESS on the Space Station is scheduled for 2007.

10.2 Mid-Term Missions

10.2.1 10m FIR/SPIRIT

There are two mid- and far-IR space telescopes under consideration with different requirements. First is a mid-IR telescope covering 5 to 50 mm with a 10 m aperture cooled to about 12 K for full sensitivity at 50 mm. This telescope mirror would need a surface accuracy of 0.36 mm rms to be diffraction limited at 5 μm, somewhat (but not much) easier than NGST which is diffraction limited at 2 mm. If NGST instruments go to wavelengths longer than 5 mm, the mid-IR telescope short wavelength requirements can be relaxed. The NGST telescope technology would be satisfactory with hopes for extension to larger aperture. It is not expected to be difficult to provide active cooling for the difference between the NGST telescope temperature around 30 K and the desired 12 K temperature. A different choice of optical materials might be made to reduce the thermal expansion differentials and maximize thermal conductivity. Possible materials include SiC or composites, such as those used for the Far Infrared and Submillimetric Space Telescope (FIRST).

The second candidate, the SPIRIT interferometer, would operate at longer wavelengths beginning at ~20 mm where increased angular resolution is a strong driver. The SPIRIT optics would also need cooling to low temperatures and would need apertures of about 3 m. The optical requirements are to provide interferometry, which implies large flat mirrors, long tracks to move them on, and an elaborate beam combination optical system with at least two telescopes. Excellent stray light rejection is essential. The beam combination system also includes beam-splitters, moving retro-reflectors, and filters to separate beams for guide star acquisition. The guide star system to provide absolute phase information will be a challenge. Research is required to determine if stretched membranes will work at cryogenic temperatures and survive in space for five or more years.

The atomic and molecular emission lines that dominate the cold Universe are extremely narrow. As a result future missions such as the 10 m FIR telescope will require spectral resolving powers of 10^6 or more. Such resolution is difficult to achieve with direct detector systems, despite their great sensitivity. As a result a variety of submillimeter and far infrared heterodyne detectors have been developed. A heterodyne system requires a local oscillator (LO) at a

precisely known frequency, and a mixer which subtracts the LO frequency from the observed signal to generate an intermediate frequency (IF) chain leading to a spectrometer. The price for this downconversion is quantum noise; the benefits are that very high spectral resolution is easy to achieve and any number of copies of the IF can be made, distributed, and processed without any loss of signal or increase of noise. This unique feature of heterodyne systems allows multi-element interferometers and aperture synthesis techniques not possible with other technologies. Improvements in noise, bandwidth, frequency coverage, and number of array elements are required for heterodyne systems.

10.2.2 HIS

The HSI scientific requirements call for a collecting area of > 500 cm^2 in the 1–170 keV band, < 10" spatial resolution, and spectral resolution equivalent to 700 km/s (at the ^{44}Ti lines at 68/78 keV) and 450 km/s (at the ^{56}Ni lines at 158 keV). To achieve these goals, HSI will utilize a depth-graded multilayer Wolter I or K-B telescope coupled to a Germanium pixel sensor. Graded multilayer mirrors offer a larger FOV and broader bandpass compared to other possible options such as microchannel plate optics or low graze angle mirrors with traditional metal coatings. Germanium sensors promise better spectral response, particularly at high energy, than room temperature solid state detectors such as CdZnTe.

Development is required both for the optics and for the focal plane sensors. To extend the mirror response to ~200 keV (considerably higher than the 40 keV currently specified for the Constellation-X hard X-ray optics) will require more complex multilayers with a larger number of layers, smaller minimum periods (< 15 Å), and small interface widths. Low-mass 10" mirror substrates are also required. Long focal lengths (20–50 m) can significantly ease the technical requirements on the optics and separated-spacecraft station keeping technology is very promising for reducing overall cost and easing technical complexity. Finally, the Germanium detectors require development of contact technologies and VLSI readouts operable at cryogenic temperatures.

10.2.3 AXIM Pathfinder

The MAXIM Pathfinder mission will be the first on-orbit demonstration of X-ray interferometry. This pathfinder will have an angular resolution of 100, more than three orders of magnitude better than *Chandra*. The interferometer baseline will be of order 1–2 m so that the optics can be fit onto one spacecraft. The beam combiner will be on the same spacecraft, 10 m from the optics. A second spacecraft placed ~500 km behind the telescope will detect the fringes using a microcalorimeter array. The second spacecraft must track the first with a lateral precision of 1mm using a laser interference pattern from the first craft. The telescope must have tens of microarcsecond pointing stability relative to the celestial sphere and will use an optical interferometer similar to that being flown on the Origins SIM to achieve this goal.

To create a synthetic aperture via X-ray interferometry, it is necessary to mix the beams from two grazing incidence optical paths in the focal plane. Each optic must be operating at the diffraction limit, and the path-length through the two telescopes must be nearly equal. The requirements on mirror figure and alignment are achievable due to the grazing incidence geometry which loosens the tolerances by ~2 orders of magnitude relative to the normal incidence case. The concept is to create pairs of diffraction limited wavefronts and steer them together at a small angle. The flatness requirement is (λHeNe/200 or better where λHeNe=6328Å). Flats of this quality are commercially available with a diameter of ~10 cm.

The feasibility of this approach was demonstrated in the laboratory in the spring of 1999, using flats to steer two X-ray beams together at the MSFC X-ray stray light facility. For the MAXIM pathfinder, the flats will need to be 1 m long to compensate for the reduction in collecting area due to the grazing incidence geometry. The plan is to work with commercial optical manufacturers to develop $\lambda/200$ (or better) flats that are ~10 cm wide and ~0.5–1 m long. In parallel with the development of large flats, it will be necessary to design and test mounts for the optics which will preserve the mirror figure in a 1 g environment for ground testing and also survive launch loads.

It is possible to build a more compact X-ray interferometer (avoiding the need for a second spacecraft 500 km behind the first) by using curved-surface optics to concentrate the beam without destroying the diffraction limited wavefront. It has been demonstrated that the required optical quality can be achieved using spherical mirrors in a Kirkpatrick-Baez mount but with relatively small collecting areas. The required collecting area could be achieved if diffraction-limited parabolic optics can be developed. Commercial ion-figuring techniques, which have been developed for figuring and polishing large optical aspheres, are the only known approach which is likely to achieve the X-ray diffraction limit with aspheric optics. Once optical flats of the necessary performance have been developed, the next logical step would be to demonstrate that X-ray diffraction-limited aspheres can be created by ion figuring.

The detectors for MAXIM pathfinder will build upon both the micro-calorimeter arrays being developed for Constellation-X and the CCDs designed for *Chandra*. The key is to make much larger arrays to increase the field of view and relax the spacecraft pointing requirements. The principal detector is likely to be a calorimeter with a 300×300 or larger array. The high energy resolution will allow optimal separation of fringes and increase the field of view. CCDs will also play a central role in the mission. A very large array is required to acquire the target through the interferometer and complete the fine pointing. If concentrating optics are used to make the mission more compact, then CCDs with micron-sized or smaller pixels will be of value.

10.2.4 EXIST

EXIST consists of a coded mask camera that will achieve a few arcminute angular resolution with high sensitivity in the 10–600 keV bandpass and a very large collecting area (~5 m^2). To meet these requirements, the detector plane must have 1 mm spatial resolution, good quantum efficiency at high energies ($E > 200$ keV) consume < 400 W. and be robust and compact. The optimal detector choice is a room-temperature, high-Z semiconductor pixel or strip sensor coupled to a low-power ASIC readout. Compared to alkali halide scintillators, high-Z solid state detectors such as CdZnTe and CdTe offer superior spatial and spectral resolution in a compact, lower mass package.

While fabrication of the coded-mask and telescope components is achievable using current technology, further development of the detectors is required in order to achieve the desired performance. CdZnTe pixel and strip detectors fabricated to date have been limited to thickness of ~2 mm, inadequate to provide good efficiency above 200 keV. Increasing detector thickness with good spectral resolution requires either development of better material with longer carrier mean-free paths or the development of good blocking contacts which will allow operation at higher bias voltages with acceptable leakage currents. In addition, because of the very large detector area and number of channels, robust packaging methods capable of being implemented on a large scale must be demonstrated.

10.2.5 OWL

The OWL mission studies ultra high-energy cosmic rays by detection of the fluorescence of atmospheric nitrogen produced by extensive air showers. The OWL satellites view the Earth's atmosphere from space to achieve a huge effective collecting area for these particles.

The development of multi-pixel photon detectors for the image plane which have good quantum efficiency over square meter areas is a key technical issue for OWL. These should also have single photoelectron sensitivity and good timing characteristics. Present detectors exist with a subset of these attributes but OWL will require cm-sized segmentation, high quantum efficiency, photon counting capability, and sub-microsecond timing in a single detector. In addition the detector must be capable of being contoured to fit a curved focal plane. Present approaches are exploring the use of multianode microchannel/microsphere plate arrays and hybrid solid state photomultipliers. The electronic readout system for this detector needs to have $\sim 10^6$ channels with low power. This will require the development of a radiation-hard custom ASIC. The timing requirements, which are < 100 ns for the single satellite version of OWL, make this development challenging. The power requirements for the detector system must be significantly reduced from those of existing systems with this large channel count and fast timing.

The optical imaging system for OWL must have an entrance aperture of ~4 m diameter with a 30 degree field of view. This places significant constraints on the type of imaging system which can be used. Present research involves the development of a UV-transmitting Fresnel lens system. This is made from a plastic material which must also be radiation tolerant. Since the nitrogen fluorescence arises in a narrow range of wavelengths, enhanced signal to noise in OWL can be provided by a large UV filter in the imaging path. Present technology development involves the identification of plastic materials which could be used for this purpose.

The background light produced in the atmosphere and by human activity in this wavelength range is not well known. Part of the development of OWL involves balloon flights of an instrument to quantify this background level.

The present satellite concept for OWL involves packaging the detector in a folded configuration for launch with deployment on orbit. The development of technology for structure deployment in space will therefore be needed for OWL.

10.2.6 ARISE

ARISE will use the space VLBI technique to achieve images with unprecedented angular resolution. The method combines data from existing ground radio telescopes with an orbiting antenna. ARISE will: (a) Image within light-days to light-months of supermassive black holes (BHs) to address accretion disc physics, relationship of the disc to the central BH, relativistic jet formation and acceleration, and the relationship of jet structures to gamma-ray emitting regions; (b) Image accretion disks in active galaxies out to 100 Mpc by means of 22 GHz water maser emission, to determine disk physics, statistical properties of disks and black hole masses, and to measure geometric distances from motions of maser spots; (c) Observe gravitational lenses to determine distance from earth to lens, providing measurement of H_0 and investigate frequency of tensing by masses in range from 10^3 to 10^8 solar masses.

To achieve these goals requires a lightweight 25 m antenna in space, with effective 0.2–0.3 mm rms surface (including correcting secondary) and high-sensitivity receivers operating between 8 and 86 Ghz. ARISE's $\sim 3{,}000 \times 40{,}000$ km orbit will produce best angu-

lar resolution of 15 microarcsec for imaging. The principal technology development requirements for ARISE are (1) lightweight 25 m inflatable antennas with good surfaces, (2) space-qualified low-noise amplifiers operating as high as 86 GHz, and (3) long-life 1 SK cryocoolers. It is important to note that suitable antennas are being developed jointly with the DoD and are a first step in NASA's Gossamer Spacecraft Program. The space-qualified amplifiers for ARISE will build on technology developed for the MAP and FIRST/Planck missions. To achieve the required sensitivity, ARISE's amplifiers will need total system noise temperatures less than or equal to 0.5 K/GHz. This implies that the ARISE receivers will have to be cooled. The current baseline is to use a mechanical pre-cooler together with a hydrogen-sorption cooler.

10.3 Vision Missions

10.3.1 MAXIM

The MAXIM mission is intended to image the event horizons around black holes, and will need an angular resolution of 0.1 microarcseconds. This implies a baseline of 100 m at 1 Å or 1 km at 10 Å. The optics will most probably have to be on separated spacecraft, formation flying with micron precision and nanometer reconstruction. TPF is facing a similar challenge and the two programs should be able to take advantage of the same technology development efforts.

An attractive feature of the MAXIM design is that angular resolution is improved through increasing the separation of the input optics and moving them away from the combiner in a linear fashion without increasing the absolute positional tolerances required. Thus, once the MAXIM Pathfinder has demonstrated a basic capability, it will be a relatively straightforward upgrade to the full up MAXIM. The major additional technology development required will be station keeping and metrology over the 100 to 1,000 m separations.

10.3.2 SPECS

The SPECS mission has a 1 km baseline but also has about the same optical requirements as the SPIRIT trailblazer mission. Its greatest advantages are at long wavelengths, 50 to 500 mm, so the optical tolerances are relaxed to 3.6 μm but the optics temperature must be reduced to about 3 K. The requirement to provide wide-field simultaneous imaging and interferometry will make very different demands on the optics when the baseline is long. This is not a matter of technology but of system design. Diffracted stray light will require more control since the far IR detectors may have a chance to view warm parts of the separated spacecraft. Also, the remote reflectors will need to be very light weight, but as they are still only a few meters in size, there should be no problem keeping them cool.

TES-based bolometers represent a significant step in the development of integrated far infrared and submillimeter focal planes, promising to reach sensitivities of 10–19 W/(Hz), which allows diffraction-limited detectors to reach the sensitivity limits set by astrophysical backgrounds for spectral resolving powers of ~100. This is truly an enabling technology for far infrared studies of the early Universe where 99% of the post big-bang photons have been emitted. These detector arrays would enable explorer-class missions of significant capability and they would be a very appealing focal plane for SPECS. At 10–19 W/sqrt(Hz), these detectors offer sensitivity about a factor of 30 greater than the present state of the art and multiplexing concepts provide comparably large benefits in format.

10.3.3 CMBPOL

CMBPOL will measure the polarization of the anisotropy in the cosmic microwave background (CMB) with an angular resolution of 0.1 degrees over a frequency range of 15 to 500 Ghz. This requires exceeding the sensitivity of the MAP satellite by 1000. The enabling technologies for CMBPOL include: 1) 100 by 100 arrays of fast nearly-quantum-limited detectors, and 2) new polarization-sensitive spectrometers based on arrays. The development of these technologies includes but is not limited to designing precision mm-wave filters, understanding multi-mode mm-wave optics, building stable lightweight 2.5 m cryogenic reflectors, and devising realtime electronic evaluation of the detector outputs.

The current trend in detector development is promising. Below 150 GHz wonderful advances have been made with MMICS (monolithic mm-wave integrated circuits). For frequencies above 90 GHz, a variety of excellent bolometer arrays are being developed. An emerging technology not to be overlooked is the photon-counting single-electron transistor.

10.3.4 ACT

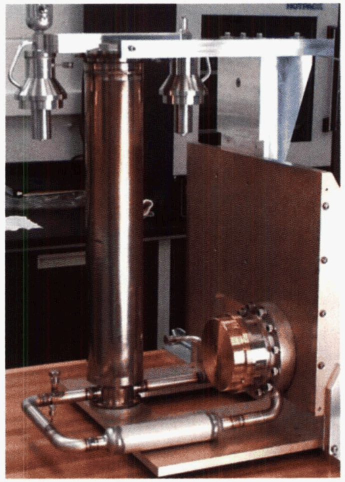
The Advanced Compton Telescope (ACT) is the next generation of gamma ray instrumentation, which will provide a dramatic improvement in sensitivity over the INTEGRAL mission. The Compton telescope has flight heritage on COMPTEL/CGRO and ACT will improve on this with roughly 50 times better sensitivity to reach a sensitivity goal of 10^{-7} photons cm^{-2} s^{-1} so as to be able to detect supernova in the Virgo Cluster of galaxies. This requires a very large area detector that is well beyond today's capabilities. The ACT consists of two detector subsystems: a tracking detector which detects Compton scatter interactions and a calorimeter to determine the energy and position of the scattered photon.

Two promising tracker concepts are a stack of silicon detectors which track the electron through several position-sensitive arrays, and a high-pressure xenon time-projection chamber which can follow the electron track by timing and position signals from a wire grid. Other ideas are likely to be developed using other detector technologies such as CdZnTe and Ge. State-of-the-art tracking detectors now achieve energy resolutions of tens of keV FWHM and energy thresholds of ~1 MeV. The goal is an energy resolution of ~2 keV or better with a threshold of 0 5 MeV or lower.

The calorimeter must have good spatial and energy resolution as well as high stopping power. In addition, it must have a minimum of inert or "passive" material (which is a source of background and energy loss), and must have a large volume for high and collecting area. Leading technologies are arrays of Ge detectors, liquid xenon time projection chambers, and arrays of CdZnTe. The goal should be to achieve an energy resolution of ~2 keV FWHM or better with 3-D spatial resolution of ~2 mm. Each of these approaches will require the development of readout electronics and the development of practical techniques for building large active volumes at low cost and power.

10.4 Enabling Cross-Cutting Technologies

We identified four technology areas that are enabling to multiple SEU missions and are truly cross-enterprise: advanced cryogenic systems, formation flying, high performance optics, and next generation detectors. These technology areas merit special attention due to their broad applicability.



Many SEU missions require cryogenic detectors, and advanced cryogenic systems such as the cooler shown here are an important cross-cutting technology.

10.4.1 Advanced Cryogenic Systems

The use of stored cryogens is being phased out as longer-life, high-reliability closed-cycle coolers become available. These new mechanical coolers will allow much longer lifetimes at reduced payload weight.

The near term (< 2007) requirement is driven by the Constellation-X mission. Constellation-X has a detector array that operates at 50 mK and with a power loading < 20 mW. To reach sub-millikelvin temperatures requires a multi-stage approach. A low-vibration mechanical pre-cooler can reach the 4–10 kelvin range and acts as a heat sink for a sub-kelvin Refrigerator.

The leading candidates for a 1.5 to 8 K cooler are a turbo-Brayton cooler (a turbine-based reverse Brayton cycle cooler) and a sorption cooler (a Joule-Thompson [J-T] cycle cooler with sorption compressors). Both of these coolers potentially have extremely low residual vibration and can meet the temperature and cooling requirements. The sorption cooler is currently in development and baselined for the Planck mission and the turbo-Brayton cooler is under development for HST/NICMOS. For both missions these are operating in the 15 to 20 Kelvin temperature range with cooling capacity in the 0.5 to 2 W region. Both refrigerators could be configured to meet the lower temperature Constellation-X requirement. But neither capability has been demonstrated and a concerted technology development effort is required to demonstrate feasibility.

Operation below 0.3 Kelvin requires either an Adiabatic Demagnetization Refrigerator (ADR) or a dilution refrigerator. The ADR is much more efficient cooler and a single-stage ADR has been delivered for *ASTRO-E* that operates from a 1.5 Kelvin liquid He cryogenic stage. Mechanical coolers will probably not be able to reach this temperature and a multistage ADR must be developed that can start from 8 Kelvin.

The mid-term (2008-2013) requirement will be cooling the large FIR telescopes to 4 Kelvin. This requires a vibration-free cooler with large cooling power (100 mW or more) in the 4–10 Kelvin range. The leading candidate for this class of coolers is again the turbo-Brayton cooler, based on the high thermodynamic efficiency of the turbo-Brayton cooler when providing large cooling loads.

10.4.2 Formation Flying

Many of the SEU missions require multiple spacecraft flying in formation to form a single telescope or detector system. These include the near term missions, Constellation-X and LISA; the medium to long term missions SPIRIT, SPECS, MAXIM; and future very large aperture X-ray missions. Of these only Constellation-X does not have a requirement to keep the individual spacecraft at precise or precisely known distances from each other.

Each mission has requirements on the measurement and control of the relative position of the spacecraft as summarized in the table below. Most of these SEU formation-flying missions are imaging interferometers with several collecting elements and a common focus which synthesize the desired large aperture. For the IR and FIR missions, the collecting elements need to be moved often (several times per day) so that the collecting elements will fill the U-V (aperture) plane. Spacecraft positions must be known to a fraction of a wavelength. For LISA, the overall formation is not controlled, but very fine local control is needed to keep each spacecraft centered on a freely falling test mass.

The formation-flying requirements for the SEU interferometer missions are similar to those for Terrestrial Planet Finder and other future interferometer missions in the Origins theme. However, unlike optical interferometers, the X-ray and submillimeter interferometers cannot use optical delay lines to adjust for small errors in spacecraft position; thus very precise spacecraft position control (at the micron level) is needed for the SEU missions. Precise spacecraft control is also needed for drag-free missions like LISA and Gravity Probe B. and the planned Satellite Test of the Equivalence Principle in the program. Precision spacecraft control also has applicability to Earth gravity-field mapping missions (such as successors to the Gravity Recovery and Climate Experiment in the Earth System Science program).

Very large-aperture X-ray missions also require formation flying in order to achieve long focal lengths (500 meters) and large collecting areas with a single mirror. The formation flying technology needed by the future SEU missions falls into four broad categories:

- Measurement of relative position of the spacecraft (distance and direction)
- Communication of position and control information between spacecraft
- Algorithms (control) for determining what position corrections are needed
- Actuators for correction of the spacecraft (or interferometer element) positions

The SEU formation flying requirements are far beyond currently demonstrated capability. The New Millennium Program ST3 mission is planned to demonstrate precision formation flying for separated spacecraft, with launch in 2004 or 2005. ST3 will use a GPS-derived radio system to measure the distance and direction to spacecraft with accuracy of a few centimeters. The spacecraft positions are to be controlled to centimeter accuracy. ST3 will also use laser ranging and direction finding to determine the distance between spacecraft with accuracy of a few nanometers.

The highest priority for SEU formation-flying missions, in terms of need of development, is in actuators. Actuators are used to adjust the positions of spacecraft or connected elements of interferometers. The actuators could be microthrusters, capable of very fine thrust; adjustable-length tethers which could efficiently allow filling of the u-v plane with a rotating set of spacecraft; or dynamic structures which would adjust the positions of interferometer elements over shorter separations. In many cases a combination of actuators will be most efficient.

Microthrusters need the ability to control ~300 kg spacecraft to ~10 nanometer accuracy over times of ~100 seconds. The thrust control needed is either for continuous thrust adjustable to ~0.1 micro-newton, or for an impulsive thruster with a thrust times duration of ~10 micro-newton-seconds. The thrust range needed is between 5 micro-newton (for fine position control) to several milli-newton (for re-arrangement of the formation to point at a new target). It is desirable to have a high propellant efficiency (specific impulse) so that large ranges of spacecraft motion (to point at numerous targets)

can be accomplished with a small propellant mass.

The second priority for future SEU formation flying missions is for measurement of distance and direction to other spacecraft. The basic capability should be demonstrated by the ST3 mission's laser ranging and direction finding capability. Development of this capability into a standard instrumentation package, possibly with a radio system for coarse positioning, would be helpful for many of the formation missions in the SEU Roadmap.

Communication of position measurements between spacecraft is important to determine which spacecraft positions corrections are needed. Communication between spacecraft can be done by various radio systems, including commercial radio modem systems. Radio modems were used between Mars Pathfinder and the Sojourner rover and are planned for use between the two ST3 spacecraft. A standardized inexpensive multi-channel space-qualified system would be useful for the future SEU interferometer missions.

The control algorithms needed for future interferometers may range from relatively simple to rather complex, depending upon the geometry and the number of spacecraft involved. Several possible control architectures could be investigated with aim towards optimization of propellant use and time between targets.

10.4.3 High Performance Optics

Mid- and Far-IR Optics

The required optical technologies and concepts include:

- Large, cold, lightweight telescope mirrors of apertures 8 m or more
- Large, cold, lightweight remote flat mirrors of aperture several meters
- Far IR beamsplitter and beam combiner systems
- Long stroke retro-reflectors, cat's eyes, or flats with very low power dissipation
- Baffling concepts for protecting cold optics from seeing warm spacecraft parts

Large, very lightweight cooled telescope mirrors and folding flats will be required. The approach will be to leverage current development, including FIRST, NGST, and SIRTF, in addition to anticipated developments for very light weight "gossamer" concepts such as stretched membrane mirrors.

Such concepts should be testable using the same facilities as NGST as apertures are actually smaller for SPECS.

Risk areas are anticipated to be in the area of mirror dynamics and stability, as the apertures must be moved in the (u-v) plane to simulate a large (~1 km) aperture.

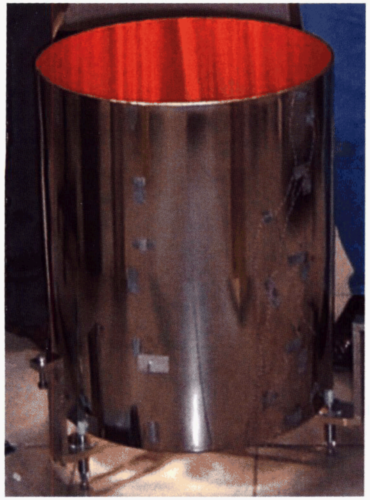
X-Ray/UV optics

The requirements on mirror figure and alignment are very tight for interferometric operation at X-ray wavelengths, but they are achievable due to the grazing incidence geometry which loosens the tolerances by ~2 orders of magnitude relative to the normal incidence case. It would be desirable to develop the capability to fabricate parabolic grazing incidence optics with diffraction-limited performance for X-rays.

For very large-area X-ray optics, a number of new technologies are required:

(i) Fabrication of Modular Mirror Segments

(a) Materials technology. Development of thin, smooth reflector substrate materials with a low mass to area ratios that permit angular resolutions of one or a few . Since the quantity of material is large, about 40,000, we require that the cost per area must be low



Many future high-energy missions rely on advanced, lightweight grazing incidence optics. A single shell is shown here.

and that it be possible to manufacture this quantity over a few year time span. The limit on launch volume constrains the length of the reflectors to perhaps 1 or 2 meters. Therefore, adjacent reflectors will be very closely spaced requiring that the material be thin to achieve a high efficiency of aperture utilization. The surface roughness of the substrate material, should be less than 7 Å rms. This can achieved either through the fabrication process itself or by polishing.

(b) Metrology and precision machining technology. Methods are needed for accurately placing and securing the substrates into the mirror segment structure and maintaining their figure. Maintenance of the figure can be achieved by a combination of imparting high stiffness to the reflector material and ingenuity in the method of retention.

(ii) Assembly of the Mirror

(a) Optical systems technology. The first aspect is the development of a system of position controllers for each modular mirror segment or group of segments that aligns them to a common focus, plus a way of performing this remotely. The second aspect is the development of a versatile integrating structure to accommodate the modular telescope segments equipped with their alignment controllers. The structure should function with any number of segments present and with missing segments.

(b) Robotic space assembly technology. The large X-ray telescope will be assembled from segments delivered in several batches. A robotic system is needed that removes the segments from the delivering spacecraft and places them into their proper location within the integrating structure. The robotic assembly system can be operated by humans on Earth through a series of commands and visual feedback.

10.4.4 Next Generation Detectors

Devices needed for detection at different wavelengths vary greatly. Nearly all missions are united by a need to detect extremely low fluxes of radiation from faint astronomical sources.

Energy resolving detectors:

- Less mechanical optical complexity
- More Cryogenic cooling complexity

Large Format Arrays:

- Offer large increases in given capability for moderate increase in system complexity
- More science per dollar

Gamma-ray and cosmic-ray detectors:

Several high-priority future gamma-ray missions require position-sensitive detectors with very good spectral resolution. These include next-generation Compton telescopes such as the Advanced

Compton telescope (ACT) and focusing mission such as the High-sensitivity Spectroscopic (HSI), designed for nuclear line measurements up to 200 keV. While CdZnTe sensors can achieve spectral resolution of 300–500 eV FWHM at energies below ~100 keV, germanium strip and pixel detectors offer the possibility of achieving 200–300 eV spectral resolution at 100 keV, with good spectral response extending to many hundred keV. For the Compton telescope application, very large detector areas (several square meters) are needed. While large volume germanium detectors, as well as millimeter pitch strip detectors have been developed and demonstrated, future gamma-ray missions require spatial resolutions of 100–300 microns.

Required detector development:

- developing contact technologies capable of producing fine pixel or strip structures in Ge and CdZnTe or other materials with similar capabilities.
- development of very low-noise ASICs to solve issues associated with the cryogenic packaging of hybrid detectors.

X-Ray detectors

Cryogenic microcalorimeters and possibly tunnel junction detectors are revolutionizing X-ray astronomy but are currently limited to small arrays and have not yet reached their theoretical resolving powers. Extensive work is needed on readout systems for large (1000×1000 and larger) arrays. TES sensors promise considerable improvements in energy resolution.

Charge-coupled device (CCD) detectors are now an established tool of high-energy astrophysics. The pioneering ASCA Solid state Imaging Spectrometer, which has been operational since 1993, demonstrated the spectroscopic imaging capabilities of the photon counting X-ray CCD. Chandra and at least three other NASA connected missions scheduled for launch within the next six months (XMM, ASTRO-E, and HETE-2) will rely heavily on this capability and other missions in various stages of development (from SWIFT to Constellation-X) plan to use CCD detectors. Although CCD detectors are in widespread use in high-energy astrophysics, there remain many areas in which technical progress is needed to meet the requirements of future missions.

CCD development:

- production of much larger arrays (of order 100 cm^2 in area) at reasonable cost
- development of detectors with much smaller pixels (1 mm or smaller)
- improved detection efficiency and spectral resolution at energies below 1 keV
- new readout strategies that readout much larger arrays (10s of megapixels) in smaller frame times (1 second or less) with reasonable electrical power

Submm/Far IR

TES-based bolometers represent a significant step in the development of integrated far infrared and submillimeter focal planes, promising to reach sensitivities of 10–19 W/sqrt(Hz), which allows diffraction-limited detectors to reach the background limits set by astrophysical backgrounds for spectral resolving powers of ~100. This is truly an enabling technology for far infrared studies of the early Universe, where 99% of the post big-bang photons have been emitted. These detector arrays would enable explorer-class missions of significant capability and they would make a very appealing focal plane for SPECS. At 10–19 W/sqrt(Hz), these detectors offer sensitivity about a factor of 30 greater than the present state of the art and multiplexing concepts provide comparably large benefits in format.

11 Conclusion

These are changing times in the nation's space science program. Old expectations and styles of carrying out space missions have vanished and been replaced by a leaner and swifter approach that is more responsive to scientific change, technical innovation, and a public mandate. These offer great opportunities to those disciplines covered by the SEU umbrella. The current program is healthier than it has ever been, as measured by the rate of scientific discovery, by the suite of missions that will soon be launched, and by public interest in the results. Now is the time to capitalize upon this success by planning with vision, realism, and flexibility for the first two decades of the next millennium.

We have created a Roadmap that provides a framework for strategic planning and technology development. It embraces a mix of proposed missions, some in a high state of technical readiness, others with equally strong scientific motivation but which will require a decade to bring to fruition. Our Roadmap is innovative in that it has broken away from the old, wavelength-specific way of doing space astronomy. However it is also balanced, representing all of the pressing scientific quests under the SEU theme and a mix of major and minor missions as well as exploiting the overlap with major initiatives covered under other themes and other space agencies.

From the dawn of creation in the big bang to the end of time at a black hole singularity, the Universe is source of inspiration and wonder for us all. We are on the threshold of solving the mystery of how it develops structure, of understanding how it evolves to allow life to appear and perhaps even flourish, and of learning what will be our ultimate destiny. The Structure and Evolution of the Universe program outlined in this Roadmap presents NASA with a balanced strategy to enable it to continue its heroic voyages of discovery well into the next century.

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